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Effects of hurricane disturbance on a tropical dry forest canopy in western Mexico☆

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ABSTRACT

Hurricanes are meteorological events with intense effects on coastal ecosystems where the change in wind kinetic energy is first concentrated. The quantification of forest change and the understanding of forest recovery trajectories after hurricane impact require a series of observations from before and after the event. Our objective was to quantify the immediate and delayed impacts of two successive large hurricanes, Jova (October 2011) and Patricia (October 2015) on the canopy structure and some ecosystem functions of the Chamela tropical dry forest on the Pacific coast of Mexico. This forest is not typically affected by large disturbance events, but has a background of extreme rainfall seasonality and corresponding phenological responses. We used a series of detailed historic and recent measurements of canopy structure and Photosynthetic Photon Flux Density (PPFD) coupled with a continuous series of remote sensing indices (NDVI) to help assemble a comprehensive view of the effects from hurricanes Jova and Patricia, category 2 and 4 in the Saffir-Simpson Hurricane Wind Scale, respectively. From ground-based LiDAR observations of canopy structure we estimated aboveground forest biomass at various times before and after the hurricanes. The net aboveground biomass loss from the two hurricanes combined (26.4 Mg ha^{-1}) was about 33.7% of the pre-hurricane value of 78.4 Mg ha^{-1}. Biomass loss from the first hurricane was about 8.6 Mg ha^{-1} (11.0% of the original). Damage from the second storm alone might have been as much as 22.7%, depending on the course of recovery between hurricanes. We also found a temporary decline in the fraction of Absorbed Photosynthetically Active Radiation (fAPAR). NDVI, well correlated to fAPAR, also showed this pattern after both hurricanes. Canopy structure was considerably altered by both hurricanes, including leaf area and persistent vertical and horizontal woody components. The effects of wind and precipitation differed in several ways: whereas biomass loss appears related to hurricane wind energy, the duration of extended greenness may be due to the extra aseasonal precipitation. Our data suggest that different aspects of ecosystem structure and function will recover at different time scales. The recovery of greenness occurs rapidly, on the order of weeks to months but canopy cover and production will recover more slowly. The re-establishment of persistent canopy structure and total biomass will likely take decades in the absence of other major disturbances or active forest management.

1. Introduction

Large disturbance from extreme weather events can have significant impacts on the structure, composition and function of terrestrial ecosystems. The effects of these events can be both obvious and subtle at immediate and delayed time scales (Foster et al., 1998; Lugo, 2008; Frank et al., 2015). The varied origin of these disturbances, their different effects, their large size and infrequent occurrence make such events challenging to study (Turner and Dale, 1998; Altwegg et al., 2017). Hurricanes (typhoons, cyclones) are meteorological events that can have particularly intense effects in coastal ecosystem, where the change in wind kinetic energy is first concentrated. Hurricane impacts on forests have been studied in numerous coastal systems (e.g., Queensland: Webb, 1958; Puerto Rico: Zimmerman et al., 1996; Van

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Bloem et al., 2005; Holm et al., 2017; Solomon Islands: Bursalem et al. (2000); Florida: Diamond and Ross, 2016; Yucatan Peninsula: McGroddy et al., 2013). These studies agree that sources of damage from hurricanes involve a mixture of driving factors, often winds and rainfall (e.g., McNulty, 2002) and a whole range of concurrent/delayed responses and cascading effects (see Gavito et al., this issue; Martínez-Ruiz and Renton, and other papers in this issue). Understanding the trajectory of forest recovery requires a series of observations, preferably initiated promptly and continued until a return to pre-hurricane conditions. Quantifying the extent of change requires observations from both before and immediately after the event (Holm et al., 2017), which though rarely feasible, is of paramount importance to assess the role of hurricanes in forest dynamics.

Patterns of hurricane damage on forest canopy functions (e.g. increase in light transmittance) and recovery (e.g. decline of transmittance toward pre-disturbance levels) vary widely. Turton (1992) found an increase of median Total Site Factor (similar to transmittance) from 3.5% before Cyclone Winifred in northern Queensland to 5.7% after six months and then 2.9% after 11 months. Fernández and Fetcher (1991) in Puerto Rico measured 3% transmittance 14 months after Hurricane Hugo – mostly caused by recent growth of pioneer plants. Bellingham et al. (1996) showed a long gradual decline in transmittance from seven to 33 months after Hurricane Gilbert in Jamaica. Sherman et al. (2001), studying the effects of Hurricane Georges on Dominican Republic mangroves, found canopy transmittance 3% before the storm, 51% after 6 months and 47% after 18 months. In the Comita et al. (2009) study of Hurricane Georges in Puerto Rico, canopy openness dropped from about 35% after the storm to about 10% eight years later. More recently, Shiels and Gonzalez (2014) found canopy opening of 16% immediately after a trimming manipulation - this value declined to backgrounds levels in about three years. This experimental study had observations before, immediately after, and through the return to pre-disturbance conditions; such a full series of measurements is not usually available for comparison.

Hurricanes are a regular climatological feature of some coastal tropical forests such as tropical dry forests (TDF). TDF represents 42% of all intra-tropical vegetation worldwide (Murphy and Lugo 1995) and is characterized by a highly seasonal rainfall pattern, which controls many ecosystem processes (Martinez-Yrizar and Sarukhán, 1990; García-Méndez et al., 1991, Jaramillo and Sanford, 1995; Rentería and Jaramillo, 2011; Anaya et al., 2012). Hurricane events have the potential for major disruption of seasonal patterns in such ecosystems. The disruption of and return to the pre-hurricane state of canopy cover is often an indicator of forest resilience (in the sense of Hodgson et al. (2015)), which implies potential changes in biomass, litterfall rates and overall forest structure.

Changes in canopy cover strongly correlate with changes in the transmittance of light to the understory, and both can be measured using satellites or ground sensor-based observations (Parker et al., 2005). Many satellites acquire spectral images on a regular basis and have been sustained over many years. This capacity provides the possibility of capturing not only the extent of change due to the event but also the long-term pattern of recovery, albeit at large scales (Negrón-Juárez et al., 2010). For example, changes in canopy cover can be assessed using satellite images taken before and after the hurricane to calculate reflectance indices such as the Normalized Difference Vegetation Index – NDVI ('greenness') and the Enhanced Vegetation Index – EVI (e.g., Wang and D'Sa, 2010). On the other hand, ground-based observations can be useful to estimate the components of Photosynthetic Photon Flux Density (PPFD) (i.e. canopy reflectance, canopy penetrance and ground layer reflectance) that are useful to estimate the PPFD fraction absorbed by the canopy (Parker et al., 2005).

Forest recovery in tropical ecosystems impacted by hurricanes involves the rapid return of leaf area to pre-disturbance levels –although much of this may involve sprouts of extant vegetation and vines. Change in biomass is often proposed as an indicator of disturbance intensity (Frolking et al., 2009). Yet, biomass change can be difficult to measure (even if there is a pre-disturbance value) because damage (loss of branches and snapped trees) is difficult to assess with allometric approaches based on intact trees. However, biomass can be usefully estimated at large-scales with various remote sensing approaches. LiDAR (Light Detection And Ranging) has proved to be a good solution (Lefsky et al., 2002; Wulder et al., 2012; Zolkos et al., 2013) as it does not suffer from saturation effects of radar or reflectance-based methods (Frolking et al., 2009; Steininger, 2000). Airborne and space-borne LIDAR systems are limited in local detail and capacity to penetrate canopies, but ground-based systems such as the Portable Canopy LIDAR (PCL, Parker et al., 2004; McMahon et al., 2015; Stark et al., 2015) can provide interior canopy detail at high spatial resolution.

In this paper we aimed at understanding the effects of recent strong hurricanes on a TDF not typically affected by large natural disturbance events, but with a background of extreme rainfall seasonality and corresponding phenological responses that are characteristic of this water-limited ecosystem. Our specific objective was to quantify the immediate and delayed impacts of two successive large hurricanes, Jova (October 2011) and Patricia (October 2015) on the canopy structure and some ecosystem functions of the Chamela forest, a well-studied TDF on the Pacific coast of Mexico. We posed three main questions: i) what was the magnitude of the hurricane effects on the vertical structure, remotely perceived reflectance, and the net exchange of PPFD (here called the 'balance') of the canopy?, ii) was the change in these properties related to measures of the hurricane intensity?, and iii) what are the implications of these findings for the time scales of recovery?

2. Materials and methods

2.1. Study site

The study was conducted at the Estación de Biología Chamela (EBCh) in the Chamela-Cuixmala Biosphere Reserve (Ceballos et al., 1999). The field station is located 2 km inland from the Pacific coast of Mexico (19° 30′N, 105° 03′W). The climate is warm (mean annual temperature 24.6 °C; 1978–2000, EBCh weather station). Mean annual precipitation is 800.4 mm (1983–2015, Maass et al., this issue). Long-term annual runoff is 99.5 mm (Maass et al., this issue) and the runoff:precipitation ratio is 0.124 (= 99.5/800.4). Potential evapotranspiration (PET) of 1130 mm was estimated for this region from the gridded climatology of New et al. (1999). There is a strong seasonality in rainfall (Bullock, 1986; Maass et al., this issue) with a 6 to 8-month dry period extending normally from November to mid-June. Tropical cyclones and the El Niño – Southern Oscillation (ENSO) add extra intra- and inter-annual variation to the precipitation regime (Bullock, 1986; García-Oliva et al., 1991; Maass et al., this issue).

The regional vegetation is predominately tropical dry forest, a 4–15 m tall, highly diverse and dense vegetation type with a well-developed understory of shrubs (Lott, 1993; Lott et al., 1987; Segura et al., 2003). The forest is old-growth, with no evidence of human disturbance (Maass et al., this issue). Most woody species in the Chamela TDF drop their leaves between October and May as a response to seasonal drought (Bullock and Solis-Magallanes, 1990). Consequently, there is a markedly seasonal pattern of leaf cover (Bullock and Solis-Magallanes, 1990), leaf area index (Maass et al., 1995), litterfall (Martínez-Yrízar and Sarukhán, 1990) and surface litter (Anaya et al., 2012).

The landscape is dominated by low-elevation (< 200 m asl) steep hills with convex slopes (López-Blanco et al., 1999). This topography controls important variation in soil moisture availability and radiation input across the landscape (Galicia et al., 1999). Structural and functional characteristics of the Chamela forest have been monitored continuously for more than 30 years on five small (12–28 ha each) contiguous watersheds (Maass et al., 2002a; Martínez-Yrízar et al., this issue). In all five watersheds, permanent plots (80 × 30 m) were established for monitoring light, tree growth, litterfall and nutrient