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Vegetation—Rainfall interactions reveal how climate variability and climate change alter spatial patterns of wildland fire probability on Big Island, Hawaii

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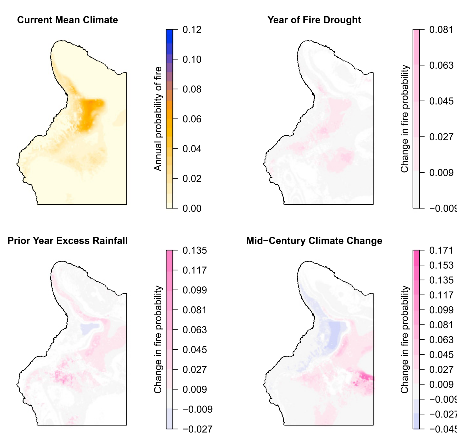
HIGHLIGHTS

- Fire is a key threat in Hawaii and other islands but predictive tools are limited.
- Spatial fire occurrence models reveal the relative influence of multiple drivers.
- Rainfall-vegetation interactions were a key predictor of fire risk variability.
- Future drying with climate change will shift peak fire risk to higher elevation.
- Fire probability will decline by populated areas but increase near high value forest areas.

GRAPHICAL ABSTRACT



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ABSTRACT

The area burned annually by wildland fire in Hawaii has increased fourfold in recent decades. The archipelago's novel fuel types and climatic heterogeneity pose significant challenges for fire risk assessment and fire management. Probability-based fire occurrence models using historical wildfire records provide a means to assess and attribute fire risk in regions of the world like Hawaii where investment in fire science is limited. This research used generalized additive models to 1) assess the relative contribution of vegetation, climate, and human-caused ignitions to the probability of fire in the northwest quadrant of Hawaii Island and 2) compare how landscape flammability varies due to interannual rainfall variability versus projected changes in mean annual rainfall (MAR) and temperature. Annual fire probability was highest for grasslands and peaked at drier conditions (0.04 at 450 mm MAR) when compared with shrublands (0.03 at 650 mm MAR) and forest (0.015 at 600 mm MAR). Excess rainfall the year prior to fire occurrence increased fire risk across grasslands, and thus overall fire probability, more so than drought the year that fire occurred. Drying and warming trends for the region under projected climate change increased maximum values of fire probability by as much as 375% and shifted areas of peak landscape flammability to higher elevation. Model predictions under future climate also indicate the largest changes in landscape flammability will happen by mid-Century. The influence of antecedent wet years on fire risk can improve near-term predictions of fire risk in Hawaii while climate projections indicate that fire management will need to be prioritized at upper elevations where high value natural resources are concentrated.

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1. Introduction

Wildland fire varies in frequency and intensity across landscapes due to the influence of climate, vegetation, and patterns of ignition (Bowman et al., 2009; Parisien and Moritz, 2009; Pausas and Keeley, 2009). Research on pyrogeography has discerned patterns in fire disturbance across geographic space from local to global scales (Bowman et al., 2014; Krawchuk et al., 2009; Murphy et al., 2013; Trauernicht et al., 2015a). These same relationships inform models of landscape flammability that integrate various predictors such as available moisture and temperature (Guyette et al., 2012; Hoyos et al., 2017), plant community structure and physiognomy (Fraser et al., 2016; Paritsis et al., 2013) as well as topography and substrate (Stambaugh and Guyette, 2008; Wood et al., 2011). These analyses contribute to both theoretical and applied aspects fire ecology. Fire-vegetation feedbacks, for instance, provide key insight into the stability and distribution of forest and savanna ecosystems (Bond and Keeley, 2005; D'Antonio and Vitousek, 1992; Murphy and Bowman, 2012; Nowacki and Abrams, 2008). Climatic thresholds of fire occurrence also help land managers and landowners identify and implement ecologically beneficial fire regimes (Schmidt et al., 2018; Twidwell et al., 2016). Landscape flammability is also relevant to understanding the risk posed by fire to valued assets and resources (Penman et al., 2014; Sturtevant et al., 2009).

By contrast, tools for wildland fire risk assessment typically draw on highly sophisticated fire behavior models in a spatially explicit framework that predict fire spread across a landscape (Ager et al., 2011; Perry, 1998; Sullivan, 2009). Fire spread models provide invaluable tools for both risk assessment and fire suppression efforts. However, in many parts of the world, limited resources and fire science capacity place real constraints on the development and validation of fire behavior models. This is especially the case on islands where novel fuels types – both endemic vegetation and completely novel, nonnative ecosystems –limit the accuracy of existing models (Beavers et al., 1999; Benoit et al., 2009; Pierce et al., 2014). In these cases, probabilistic approaches to modeling fire occurrence that use observed burned areas or historical fire records may reduce the number of assumptions underlying more complex fire spread models (Brillinger et al., 2006; Preisler et al., 2004). Applications of this approach range from stand level burn patterns based on vegetation and microclimatic factors (Gonzáles et al., 2006; Trauernicht et al., 2012) to regional analyses that integrate fire records, climate, weather, and land cover data (Dickson et al., 2006; Hoyos et al., 2017; Parisien and Moritz, 2009; Paritsis et al., 2013). A further advantage is that probabilistic approaches often allow models of fire occurrence to be parameterized from existing datasets (Bremer et al., 2018; Preisler et al., 2004).

Hawaii and other Pacific Islands provide some of the clearest evidence of both historical and contemporary fire-driven shifts from forest to savanna vegetation due to anthropogenic fire (Dodson and Intoh, 1999; Ellsworth et al., 2014; Perry et al., 2012; Trauernicht et al., 2015b). These derived savannas (sensu Veldman and Putz, 2011) appear to represent highly resilient, alternative ecosystem states (Tepley et al., 2018; Yelenik and D'Antonio, 2013) and support high frequency fire regimes compared to relatively infrequent fires in native ecosystems prior to human arrival (Athens and Ward, 2004; Burney and Burney, 2003; Perry et al., 2012). The extent of area burned annually in Hawaii has increased four-fold in recent decades, rivaling the western US in terms of the percentage of land area affected annually (Trauernicht et al., 2015b). This change in fire regime is driven by strong rain shadows, episodic drought, and frequent human-caused ignitions, combined with agricultural abandonment which has left large-scale, continuous beds of fine fuels covering a third of the archipelago's undeveloped land surface (c. 4000 km^2; Hawbaker et al., 2017). With lightning strikes relatively rare on oceanic islands and prescribed or managed burning largely ceasing in Hawaii with the closure of large-scale sugarcane plantations in the past decade, the vast majority of fires are caused by humans either accidentally or as arson (Trauernicht et al., 2015b). Although >80% of the area burned annually in Hawaii is constrained to nonnative, derived savannas (Hawbaker et al., 2017), the novel fire regime exposes both residential areas and forested ecosystems to fire impacts. Native ecosystems in Hawaii are particularly sensitive in that fire disturbance typically favors nonnative species establishment leading to native species and habitat loss and long-term conversion to more fire-prone vegetation (Ainsworth and Kauffman, 2013; D'Antonio et al., 2017; LaRosa et al., 2008; Trauernicht et al., 2018).

Despite plot- and site-level evidence of increasing flammability in Hawaii (Ainsworth and Kauffman, 2013; D'Antonio et al., 2011, 2017; Hughes et al., 1991), few studies examine how savanna expansion alters the spatial patterns of fire for island landscapes (D'Antonio et al., 2000; Ellsworth et al., 2014; Perry and Enright, 2002), nor how fire occurrence may be modulated by spatial and temporal climate variability (Chu et al., 2002; Dolling et al., 2005; Van Beusekom et al., 2018). In Hawaii, this is due, in part, to limited investment in fire research and risk assessment tools relative to the continental US as well as sparse weather data relative to the islands' radical climate variability (Weise et al., 2010). As elsewhere in the tropics, Hawaii also presents challenges in terms of predicting future changes in landscape flammability. Locally downscaled climate projections are largely boiled down to mean annual variables, such as temperature and rainfall, whereas fire risk is more influenced by the extremes, or tails, in the distribution of these conditions. In temperate ecosystems, future fire occurrence is linked to increasing duration of the fire season, or the hotter, drier climatic conditions under which fire is most likely, under warming temperatures (Jolly et al., 2015; Moritz et al., 2012; Westerling et al., 2006). In contrast, understanding shifts in fire activity due to climate change in the tropics is constrained both by the lack of research establishing climatic and weather thresholds for fire occurrence as well as the limited ability of climate models to capture changes in the El Niño-Southern Oscillation and rainfall seasonality such as the Asian Monsoon (Huang et al., 2013; Turner and Annamalai, 2012; Vecchi and Wittenberg, 2010), which are strong drivers of variation in tropical fire regimes (Chu et al., 2002; Gill et al., 2000; Van Der Werf et al., 2008). Coarser climatic variables like mean annual rainfall may still constrain and promote fire activity, creating climatic 'sweet spots' for fire (Bradstock, 2010; Murphy et al., 2011). Therefore, examining the relative influence of climate variability and average climatic conditions on fire occurrence remains a key task for understanding how landscape flammability varies in the tropics.

In response to the limited availability of landscape-scale analyses of fire occurrence and direct requests from land managers and ecosystem service modelers for improved assessments of fire risk in Hawaii, a modeling framework was developed that draws on fundamental fire regime concepts (i.e., pyrogeography; Krawchuk et al., 2009; Bowman et al., 2014) and existing data sets to model the probability of fire occurrence across a large (3000 km^2) landscape encompassing the northwest quadrant of the 'Big Island' of Hawaii. The research objectives were: 1) to develop a model of fire occurrence to assess the relative contribution of vegetation, climate, and ignitions to the probability of fire for the region; and 2) compare how landscape flammability varies due to interannual rainfall variability vs. longer-term projected changes in mean annual rainfall and temperature.

2. Materials and methods

2.1. Study region

We selected the northwest quadrant of Hawaii Island (a.k.a. "Big Island") for this analysis primarily because it provides the longest history of wildland fire burned area records (i.e., fire scar maps) for the state of Hawaii (Castillo et al., 2003). The region also contains watersheds of interest in two related, interdisciplinary assessments of biophysical, economic and cultural landscape values (Bremer et al., 2018; Wada et al.,