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The Contemporary Scale and Context of Wildfire in Hawai‘i¹

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Abstract: Wildfire is a major threat to natural resources and native species in Hawai‘i, but the frequency and extent of wildfires across the archipelago has not been well quantified. Our objective was to summarize the available wildfire data for Hawai‘i and synthesize the social and ecological dimensions of wildfire drivers, impacts, and management responses. We constructed a 110-yr span of wildfire records for the state of Hawai‘i to examine historical trends (1904–2011) and summarized relationships between contemporary wildfire occurrence (2005–2011) and land use/land cover types and human population. Total area burned statewide increased more than fourfold from 1904 to 1959 to peaks in the 1960s–1970s and mid-1990s to present. From 2005 to 2011, on average, 1,007 wildfires were reported across the state per year (± 77 SE), burning an average of 8,427 ha yr⁻¹ ($\pm 2,394$ SE). Most fires (95%) were <4 ha, while most area burned (93%) was attributed to fires ≥ 40 ha. Ignition frequency was positively correlated with human population across islands. Wildfires were most frequent in developed areas, but most areas burned occurred in dry nonnative grasslands and shrublands that currently compose 24% of Hawai‘i’s total land cover. These grass-dominated landscapes allow wildfires to propagate rapidly from areas of high ignition frequencies into the forested margins of the state’s watersheds, placing native habitat, watershed integrity, and human safety at risk. There is an urgent need to better assess fire risk and impacts at landscape scales and increase the integration of prefire planning and prevention into existing land management goals.

RESEARCH ON THE interaction between nonnative grasses and fire in Hawai‘i has brought widespread attention to the impacts of novel wildfire regimes on native ecosystems globally (D’Antonio and Vitousek 1992). Yet the extent to which wildfire has become a pervasive feature of Hawai‘i’s landscapes has not been well quantified. Wildfire in Hawai‘i differs greatly from that of most of the continental United

States in that fire occurs year-round (Chu et al. 2002) and is supported by vast, unbroken expanses of highly fire-prone, nonnative ecosystems dominated by invasive grasses and other fire-adapted plants (Elmore et al. 2005, Varga and Asner 2008, Ellsworth et al. 2014) (Figure 1). These nonnative species regularly encroach into Hawai‘i’s native ecosystems, which contain one of the world’s highest rates

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FIGURE 1. Fires in nonnative grasslands in Hawai'i illustrating (a) a high intensity, experimental fire in guinea grass (*Megathyrsus maximus*) in which flame heights reached 4–5 m (poles at right are 3 m) under relatively benign environmental conditions (i.e., 8 km hr⁻¹ winds, 70% relative humidity) (photo by C. Trauernicht); and (b) high fuel bed continuity evident in an aerial photo of a relatively low intensity wildfire burning in fountain grass (*Cenchrus setaceus*) (photo by E. Moller).

of species endemism and the largest proportion of endangered plant species in the United States, where they suppress native plant regeneration, increase ecosystem flammability and fire frequency, and accelerate rates of habitat loss (Hughes et al. 1991, Smith and Tunison 1992, Ainsworth and Kauffman 2013, D'Antonio et al. 2011). There is growing concern among natural resource managers, fire responders, researchers, and landowners about wildfire impacts (DOFAW 2010). However, resources for prefire mitigation and wildfire response in Hawai'i are limited and, given the state's geographic isolation, Hawai'i lacks access to the impressive array of inter-agency support for fire management available on the mainland United States (DOFAW 2014).

The human dimensions of wildfire in Hawai'i have also received little attention despite the dominance of human-caused ignitions and the contribution of land use change to the current extent of fire-prone, nonnative ecosystems. Before human arrival, wildfire ignition sources in Hawai'i are thought to have been limited to volcanic activity and infrequent dry lightning strikes. In line with this, soil charcoal evidence suggests wildfires were infrequent with highly localized effects (Smith and Tunison 1992, Burney et al. 1995), and as a result, many native Hawaiian plants have

limited adaptations to fire as a frequent ecological disturbance (LaRosa et al. 2008, but see Vogl 1969). Humans have increased wildfire occurrence across the archipelago both by greatly increasing ignitions and by introducing fire-prone plant species, especially nonnative grasses. Especially in dry and mesic areas and in all ecosystem types during droughts (Dolling et al. 2005, Cram et al. 2013), these factors currently drive recurrent wildfires in Hawai'i that incur ecological and socio-economic costs in terms of watershed function, natural resource degradation, community safety, and emergency response (DOFAW 2010, 2014).

The first reported "disastrous" wildfire in Hawai'i was an escaped agricultural fire in 1901 that burned >12,000 ha of agricultural and forested lands over 3 months on the Hāmākua Coast of Hawai'i Island (Commissioner of Agriculture and Forestry 1903). The Hāmākua Fire directly led to the establishment of Hawai'i's Forest Reserve System, the integration of wildfire into government forest management policy, and the initiation of annual wildfire reporting in 1904. Previous studies have summarized statewide wildfire frequency and extent (Burgan et al. 1974, Cuddihy and Stone 1990, Chu et al. 2002, Weise et al. 2010); however, they have not covered the full range of records and, until now,

there has been no available information on spatial patterns of fire occurrence. Our objectives are to synthesize previously available wildfire information along with a newly available, spatially explicit wildfire history for Hawai'i (HWMO 2013*b*) to describe: (1) wildfire frequency, extent, and long-term trends; (2) social, ecological, and historical factors contributing to wildfire risk; (3) ecological and social impacts of wildfire; (4) responses to reduce wildfire impacts; and (5) recommendations for fire management and science moving forward.

MATERIALS AND METHODS

All analyses consider only wildfires, defined here as unplanned, wildland fires as opposed to prescribed, experimental, or structure fires. We drew on multiple sources of fire history data to achieve the first objective of summarizing wildfire frequency, extent, and long-term trends across Hawai'i's six major islands—Kaua'i, O'ahu, Maui, Moloka'i, Lana'i, and Hawai'i Island. The lack of reporting, especially of small wildfires among earlier records, can be problematic when compiling and analyzing fire histories. In addition, the data sets do not include wildfires set by training exercises on military lands that result in numerous ignitions on O'ahu and Hawai'i Islands (Beavers et al. 1999, Beavers and Burgan 2002). Therefore, the available data provide conservative estimates of wildfire occurrence.

We used annual area burned to examine historical trends (1904–2011) in wildfire occurrence because it is less sensitive to under-reporting of small fires as large fires typically account for >90% of total area burned (e.g., Niklasson and Granström 2000). Annual summaries of area burned were drawn from three sources: (1) a compilation of Hawai'i territorial and state reports of total area burned by wildfire for 1904–1977 by Schmitt (1977; Schmitt data set hereafter); (2) Hawai'i Division of Forestry and Wildlife annual reports for 1994–2007 (available online at <http://dlnr.hawaii.gov/forestry/fire/data/>; DOFAW data set hereafter); and (3) the first spatially explicit (i.e., records with incident locations) fire history for Hawai'i state for 1967–2012 compiled

from agency records by the Hawai'i Wildfire Management Organization (HWMO 2013*b*; HWMO data set hereafter).

The Schmitt data set and the government fire reports upon which it was based have been cited in previous publications (Burgan et al. 1974, Cuddihy and Stone 1990). Over the 73-yr time span in the Schmitt data set, 9 yr were missing data and 10 yr provided underestimates of total area burned as not all fire reports included fire size. These underestimated values are indicated and presented in the results (Figure 2) but were excluded from all analyses of trends in wildfires over time. There were also eight instances in the Schmitt data set where total area burned was reported for a 2-yr time span (due to biennial reporting), in which case, we split the value and allocated half of the area reported to each of the 2 years. The DOFAW data set provided statewide annual summaries of total area burned and number of fires from 1994 to 2012. However, data after 2007 were excluded as reports ceased to include county agency records after 2007 (W. Ching, pers. comm.).

In contrast to the Schmitt and DOFAW data sets in which only annual summaries were available, the HWMO data set provided records of individual wildfire incidents from all county, state, and federal fire response agencies with the exception of the Department of Defense (Pierce and Pickett 2014). The HWMO data set contained state (DOFAW) records spanning the 47-yr period from 1967 to 2013 and National Park records from 1922 to 2012, but complete county fire department records were available only from the early to mid-2000s. The HWMO data set included date of occurrence and fire size for 12,906 wildfires, with spatial locations of ignitions for 11,109 reported fires (86% of total) derived from GPS coordinates, maps, and/or narrative accounts. The cause of ignition was reported for 6,218 reported fires (48% of total).

To examine temporal trends in wildfire occurrence over the past century in Hawai'i (1904–2011), we combined the Schmitt, DOFAW, and HWMO data sets and used a linear mixed model of area burned (transformed to area^{0.2} to meet assumptions of homogeneity of variance) as a function of year

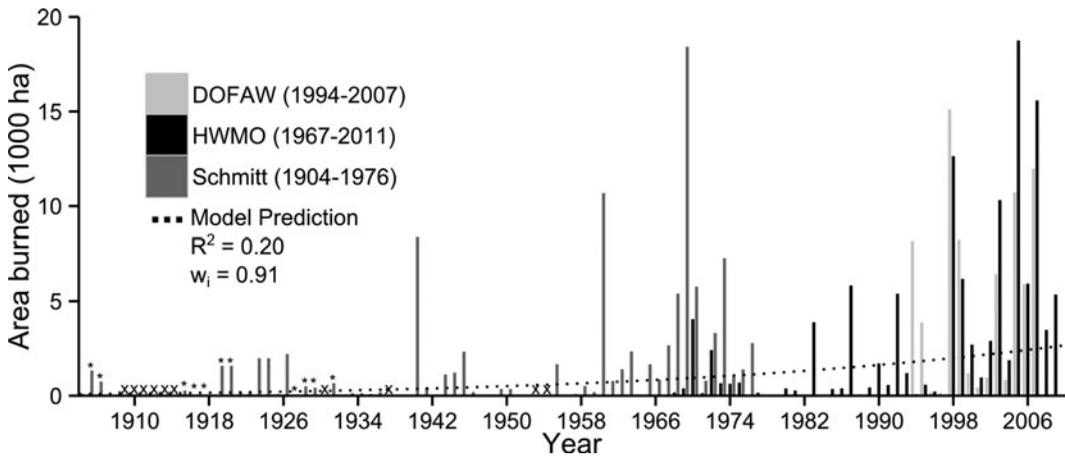


FIGURE 2. The available statewide record for annual area burned spanning 1904–2011 using combined data sets from Schmitt (1977), online Hawai'i Division of Forestry and Wildlife (DOFAW) reports, and the Hawai'i Wildfire Management Organization (HWMO). Data were analyzed using a linear mixed model (dashed line) of area burned (transformed to $\text{area}^{0.2}$) as a function of year with data source as a random effect and assessed against the null model using Akaike's information criterion (explained deviance [R^2]=0.20; Akaike's weight [w_i]=0.91). In the case of biennial reporting (8 records in Schmitt's data set), we split the biennial area burned value and allocated half of the area reported to each of the 2 yr. Missing data points are indicated by "x," and years with underestimates of area burned are indicated by asterisks (*) and were excluded from the analysis.

with data source as a random effect. Instead of arbitrarily excluding records for overlapping years, we analyzed all available records for all years with data source as a random effect and included a temporal correlation term in our models (Pinheiro and Bates 2000). The random effect accounted for expected variation in the slope and intercept among data sets while providing a prediction of any overall temporal trend supported by the data, whereas the correlation term accounted for temporal autocorrelation inherent in having multiple observations for overlapping years. Years for which area burned was underestimated in the Schmitt database were excluded from the analysis.

To summarize current wildfire conditions statewide, we used records from the HWMO data set spanning the years 2005–2011 for which complete records from all agencies were available ($N=7,054$). We first calculated mean values (± 1 SE) for number of ignitions and area burned per year for this 7-yr time span, both across all records as well as across fire size classes as defined by the National Wildfire Coordinating Group (Table 1). We also calculated mean values (± 1 SE) for number of

ignitions and area burned across months to characterize interannual variation. We used information on the cause of ignition across all years in the HWMO data set to calculate the percentage of fires resulting from natural causes, arson, or accidental human activities.

We also examined the spatial distribution of total wildfire ignitions and total area burned

TABLE 1
Wildfires in Hawai'i over the 2005–2011 Period:
Wildfire Size Classes Based on National Wildfire
Coordinating Group Categories

Fire Size Class (ha)	Fires (yr^{-1})	Area burned (ha yr^{-1})
<0.1	709 (± 40.2)	27.4 (± 2.7)
0.1–<4	247.9 (± 39.3)	150.6 (± 22.3)
4–<40	32.3 (± 5.8)	387.5 (± 69.3)
40–<160	8.1 (± 2.1)	499.6 (± 128.8)
160–<400	6.1 (± 1.3)	1,129.7 (± 256)
400–<2,020	3.6 (± 0.9)	3,044.6 (± 737.4)
>2,020	0.7 (± 0.3)	3,187.7 ($\pm 1,465$)
Total	1,007 (± 77.1)	8,427.0 ($\pm 2,394.0$)

Note: From 2005 to 2011, most wildfires (95%) in Hawai'i were 4 ha or smaller, whereas fires >40 ha accounted for 93% of the total area burned. Values reported are statewide means (± 1 SE).

across newly revised Hawai'i gap analysis (HIGAP) land use/land cover (LULC) types in a geographic information system (Gon et al. 2006; unpubl. revisions by J. Jacobi). Importantly, because each record in the HWMO data set represents a single ignition point attributed with area burned, these summaries provide a relative description of area burned across LULC types as opposed to absolute values for the extent of each LULC affected by fire. We also used the spatial distribution of wildfires from the HWMO data set to examine the correlation between ignition density (fires km^{-2}) and population density per island for the six largest islands in the archipelago. In order to place Hawai'i's wildfire summary in a national context, we compared the percentage of total land area burned annually in Hawai'i with that of the entire continental United States (including Alaska) and the 12 western-most states for each year from 2005 to 2011 using data from the National Interagency Fire Center (WMFI 2012).

We used the results from these methods along with the available literature and discussions with various fire response and land management professionals to address the remaining objectives in the Discussion: (2) contributing factors; (3) impacts; (4) responses; and (5) future directions for fire management

in Hawai'i. Nomenclature for all plant species referred to is derived from the Missouri Botanical Garden's Tropicos database (<http://www.tropicos.org/>).

RESULTS

Temporal patterns across the three available statewide fire history data sets indicated a variable but overall increasing trend in annual area burned over time (Akaike weight [w_i] >0.99 , $R^2=0.28$) (Figure 2). Fire activity remained relatively consistent for the first half of the twentieth century after which there were two dramatic increases in area burned. The first occurred in the late 1960s and early 1970s, peaking in 1969 at 18,423 ha. The second began to increase in the late 1990s and peaked at 18,752 ha in 2005.

The HWMO data set for 2005–2011 indicated Hawai'i experienced an annual average of 1,007 (± 77 SE) wildfires, burning on average 8,427 ha yr^{-1} ($\pm 2,394$ SE). Ninety-five percent of these wildfires were <4 ha in size, but 93% of the area burned annually resulted from wildfires >40 ha in size, which accounted for only 1.8% of total ignitions (Table 1). Ignitions occurred year-round with peaks in the summer (June, July, August) and winter months (January, December), whereas area

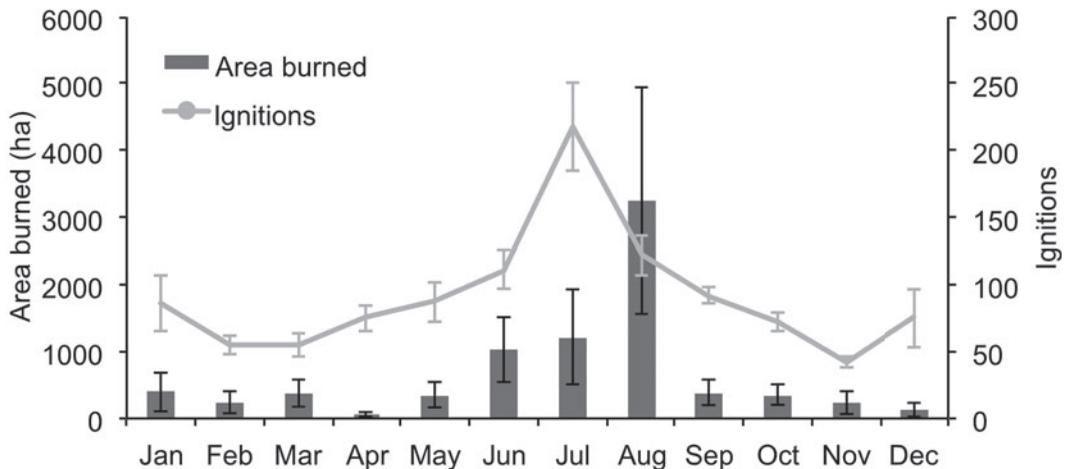


FIGURE 3. Mean monthly wildfire ignitions and area burned (± 1 SE) in Hawai'i over 2005–2011 ($N=7,054$) (HWMO 2013a) illustrate year-round wildfire occurrence with ignition peaks in July and December/January and peak area burned during drier, summer months.

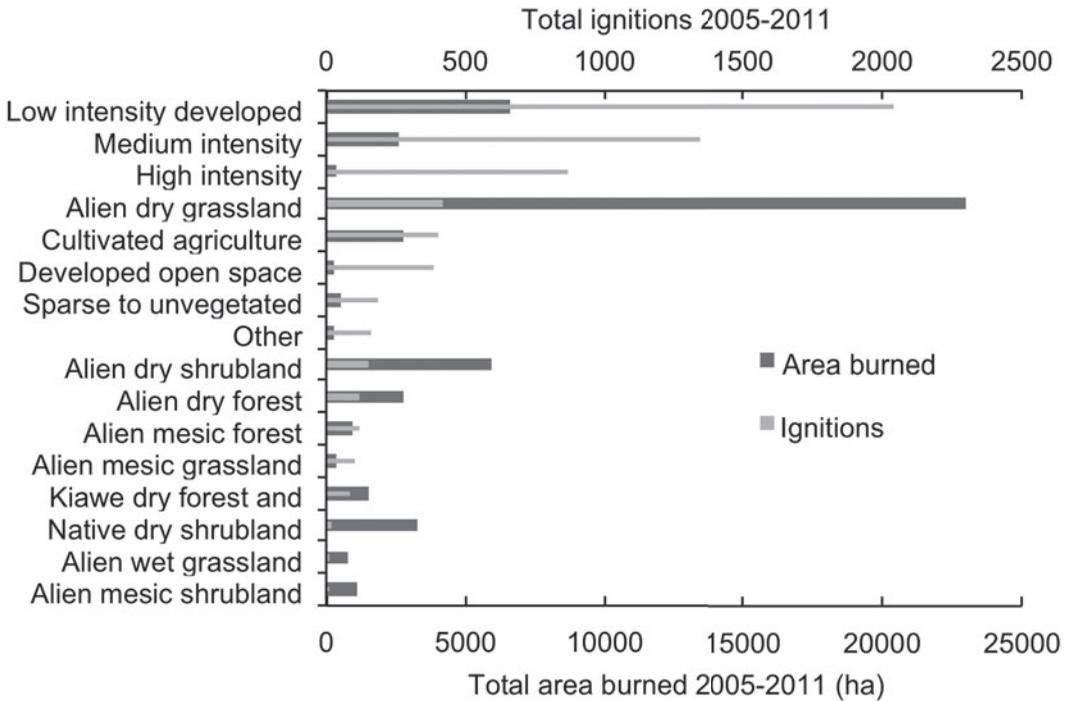


FIGURE 4. In Hawai'i over the period 2005–2011, the majority of wildfire ignitions (light gray bars) occurred in developed areas (66%), whereas the majority of area burned (dark gray bars) occurred in dry grasslands and shrublands dominated by nonnative grasses (54%). Land use/land cover classes are from Gon et al. (2006, with unpubl. revisions by J. Jacobi) and wildfire records are from HWMO (2013a) ($N=7,054$).

burned showed a large increase during the summer months (Figure 3).

Among the 6,218 fires for which cause of ignition was reported, 81% were listed as undetermined or unknown, 16% were attributed to human accidental causes (e.g., campfires, welding, vehicle engines), 2% were listed as arson, and 1.5% were attributed to natural causes (lightning and lava). The spatial distribution of wildfire ignition and area burned across LULC types from 2005 to 2011 revealed very high numbers of ignitions in developed areas, and ignition density was highly correlated with population density across islands (Pearson's $\rho=0.99$) (Figure 5). This relationship still held (Pearson's $\rho=0.86$) when O'ahu was excluded as a potential outlier due to its extremely high population density. Most of the area burned was attributed to dry, nonnative ("alien") ecosystems, especially dry, nonnative grasslands (Figure 4).

The mean annual area burned in Hawai'i from 2005 to 2011 ($8,427 \text{ ha yr}^{-1}$) accounted for 0.48% of Hawai'i's total land area, which was greater than the proportion of land area burned across the entire U.S. mainland (0.30%), and even across the 12 states in the fire-prone, western United States (0.46%, including Alaska) over this same time period (WMFI 2012). Even for two of the worst fire years on record for the continental United States in terms of area burned, Hawai'i had a larger percentage of its land area burned (WMFI 2012) (Figure 6).

DISCUSSION

The synthesis of the Schmitt, DOFAW, and HWMO data sets provides the most complete summary of wildfire occurrence for the state of Hawai'i to date. The first five decades (1904–1959) of records average only 800 ha

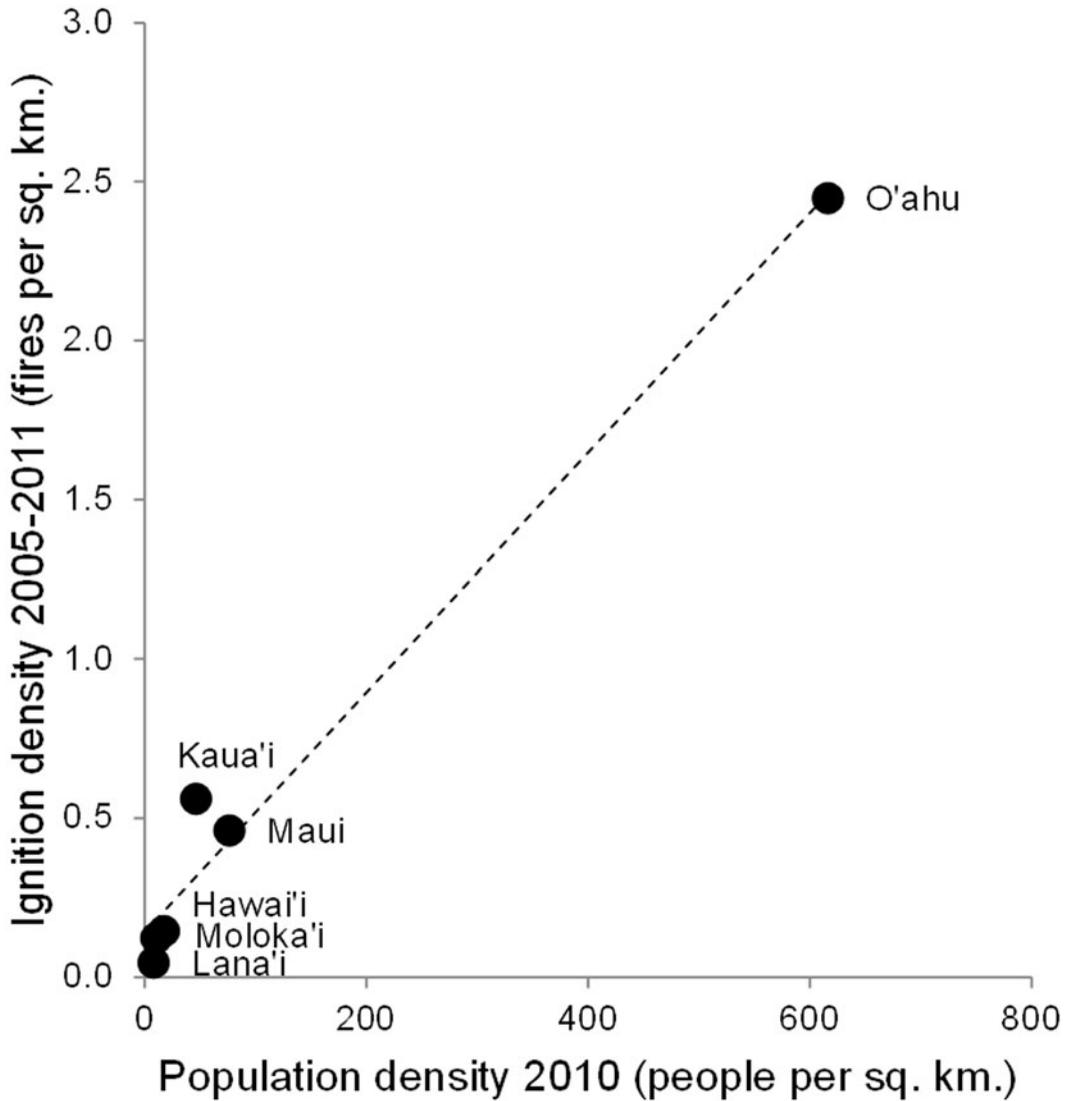


FIGURE 5. There is a strong correlation (Pearson's $\rho=0.99$) between population density per island (from 2010 U.S. Census) and the total ignitions per square kilometer during 2005–2011 ($N=7,054$) (HWMO 2013a). The overall pattern remains intact when O'ahu is removed from the analysis, although the correlation is slightly weaker (Pearson's $\rho=0.86$).

burned per year and suggest incidents such as the 12,000 ha Hāmākua Fire of 1901 were rare events. Most available evidence indicates that, prior to human arrival, fires were infrequent and largely restricted to active volcanic events (Smith and Tunison 1992, Burney et al. 1995). The dramatic historical increase in area burned (Figure 2) and the current prevalence

of wildfire in Hawai'i (Table 1)—especially relative to the archipelago's limited land area (16,636 km²) (Figure 6)—indicate that the transformation of Hawai'i's landscapes since human arrival has greatly increased wildfire occurrence. Fire was undoubtedly a principle agricultural tool of early Polynesian settlers in Hawai'i; however, the introduction of most

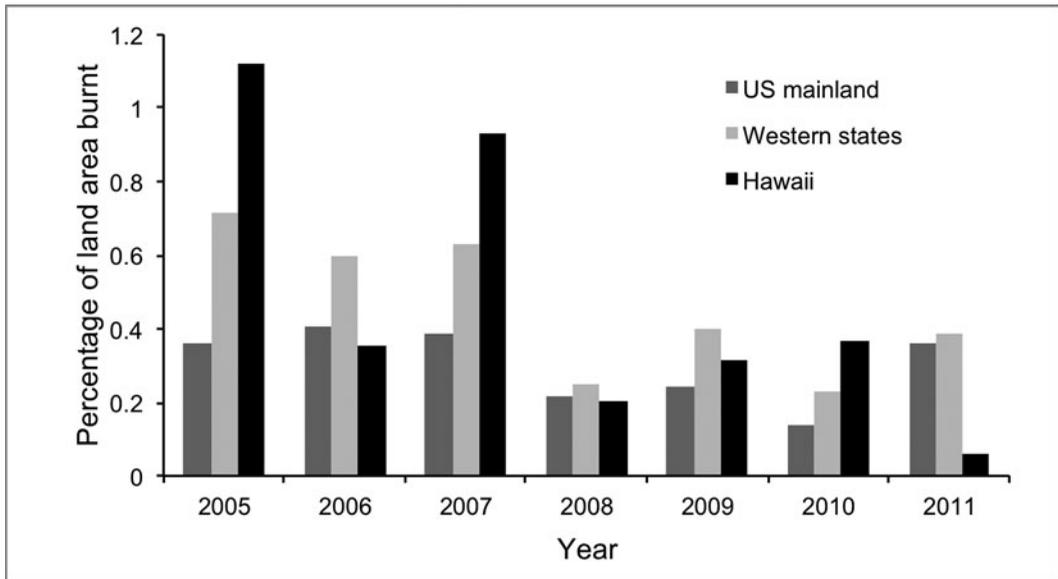


FIGURE 6. The annual area burned as a percentage of total land area in Hawai'i (black bars) was on par or exceeded the 12 western-most states of the United States, including Alaska (light gray bars), and the United States as a whole (dark gray bars) for all years in the 2005–2011 period except 2011 (WMFI 2012). The years 2005, 2006, 2007, 2011, and 2012 (not shown) were the worst wildfire years on record for the continental United States in terms of total area burned.

fire-prone species (e.g., African pasture grasses) and large-scale conversion of native ecosystems occurred well after European contact, near the turn of the nineteenth century. We therefore first draw on the spatial patterns of wildfire from the HWMO data set to understand the consequences of these changes in the context of ignitions, fuel availability, and climate—the fundamental drivers of wildfire occurrence (Bond and Keeley 2005). We then consider the current ecological and socioeconomic impacts of wildfire, Hawai'i's capacity for wildfire response and management, and, finally, point to current efforts to improve wildfire management in the state.

Contributing Factors: Human-Caused Ignitions

People are the primary driver of wildfires in Hawai'i. Natural causes of ignition are rare, with lava currently restricted to active flows on Hawai'i Island, and lightning strikes accounting for <0.2% of attributed wildfire causes. The influence of people also supported

the high frequency of ignitions in developed areas (Figure 4) and the strong, positive correlation with island population (Figure 5). The development of Hawai'i's agricultural economy from the mid-nineteenth to early twentieth centuries accelerated population growth and likely had significant impacts on the number of wildfire ignitions. However, the arrival of Polynesians as recently as 800 yr ago (Wilmshurst et al. 2011) likely marked the first significant increase in wildfire activity in Hawai'i (Kirch 1982, Cuddihy and Stone 1990). In addition to agricultural uses, there are accounts of larger-scale, intentional landscape burning to manage plant resources such as the native pili grass (*Heteropogon contortus*) for thatching, and other plants for food and animal fodder (McEldowney 1979, Kirch 1982). The effects of repeated, intentional burning on vegetation in Hawai'i were likely similar to patterns observed elsewhere in the Pacific. Burning by Maori in New Zealand (McWethy et al. 2010), by Fijians on Viti Levu (King 2004), and by Micronesians in Yap and

Guam (Dodson and Intoh 1999, Athens and Ward 2004) was—and on some islands continues to be—used for farming and natural resource manipulation and has resulted in the expansion of fire-adapted vegetation types (e.g., savannas). Given the scarcity of dry lightning strikes, it is possible that fire management by Hawaiians also maintained certain grassland and shrubland areas with native, fire-tolerant species such as pili grass (e.g., Daehler and Goergen 2005).

Contributing Factors: Fuel Availability and Landscape Change

The current predominance of area burned among Hawai'i's nonnative grasslands and shrublands illustrates how changes in land cover, especially since European arrival, have also contributed to increases in wildfire occurrence (Figure 4). Nonnative grasslands and mixed nonnative grasslands/shrublands are currently the state's most extensive vegetation type, covering 24% of the total state land area (>400,000 ha) (revised HI-GAP, Gon et al. 2006). These areas are dominated by highly invasive, fire-prone grasses introduced by Europeans since at least the nineteenth century (Ripperton et al. 1933) such as guinea grass (*Megathyrsus maximus* [Jacq.] B. K. Simon & S. W. L. Jacobs), fountain grass (*Cenchrus setaceus* [Forssk.] Morrone), molasses grass (*Melinis minutiflora* P. Beauv.), and buffel grass (*Cenchrus ciliaris* L.). These species form continuous, nearly monotypic fuel beds, ignite easily, attain extremely high fine fuel loads, and are capable of resprouting and/or establishing from seed more vigorously in the postfire environment than is the majority of native vegetation (Freifelder et al. 1998, Beavers et al. 1999, Castillo et al. 2003, Ellsworth et al. 2014). Nonnative grasses also readily invade existing native woodlands (D'Antonio et al. 2000, Litton et al. 2006, D'Antonio et al. 2011), with some species capable of colonizing young, barren lava flows. Grass invasions elsewhere in both temperate and tropical ecosystems have led to similar ecological changes in terms of increasing fine fuel loads and continuity and increasing resultant fire intensity (Platt and Gottschalk 2001,

Rossiter et al. 2003, Hoffmann et al. 2004, Veldman and Putz 2011). In Hawai'i, the extensive area covered by nonnative grasses (Elmore et al. 2005, Varga and Asner 2008) (Figure 1) supports frequent wildfires that kill woody plants and erode the margins of forested areas, leading to increased grass cover, forest contraction, and often forest fragmentation (Blackmore and Vitousek 2000, Ellsworth et al. 2014). This invasive grass-wildfire cycle has had large impacts on native dry forest and increasingly threatens mesic forests as well (D'Antonio and Vitousek 1992, Ellsworth et al. 2014).

In addition to increasing wildfire risk in remote areas, fire-prone grass species are now prevalent in much of the state's "wildland-urban interface" (WUI)—defined as the transition between developed and unoccupied land (Butler 1974)—which, in Hawai'i, extends from areas where most of the state's population resides at lower elevations, upward into the lower margins of forested watersheds (HWMO 2013a). In contrast to WUI issues on the U.S. mainland, where the risk to valued resources posed by wildfire has increased as development pushes into native, fire-prone habitat, the increasing wildfire risk in Hawai'i's WUI is more closely linked to agricultural abandonment and the expansion of fire-prone vegetation, primarily nonnative grasses. Land use in Hawai'i underwent extensive change with the privatization of land in 1848, the disintegration of traditional Hawaiian systems of watershed-scale land management (Kame'eleihiwa 1992), and the establishment of large-scale plantation agriculture and ranching. By the mid-twentieth century, active grazing lands had expanded to nearly 850,000 ha (>50% of total state land area) and sugarcane to more than 90,000 ha (>5% of state land area) (Schmitt 1977). The sugar industry also introduced the preharvest burning of cane fields, which may have increased the risk of escaped fires; however, the centralization of landholdings also simplified access and communication for wildfire response via the cooperation of plantation fire wardens with state agencies (DOFAW 2010).

More recently, Hawai'i has undergone major declines in ranching and plantation

agriculture. Between peak production estimates in 1959–1960 and surveys in 2012, active cropland declined by 65% from >200,000 ha to 70,000 ha, and active grazing lands declined by 62% from 850,000 ha to 324,000 ha (Schmitt 1977, USDA 2012). It is estimated that 90% of the >760,000 ha of suitable agricultural land in Hawai'i is currently fallow (Suryanata 2002). Unmanaged, fallow agricultural lands in Hawai'i typically become dominated by nonnative grasses (e.g., Cramer et al. 2008, Veldman and Putz 2011), making agricultural abandonment a primary driver of the current dominance of fire-prone, nonnative grasslands statewide (e.g., 24% of state land cover). Many of these lands are adjacent to housing and other infrastructures, which increases both the probability of ignitions and wildfire risk for communities. Furthermore, as agricultural lands go unmanaged, access roads and critical water resources (i.e., irrigation canals and reservoirs) become degraded, further complicating wildfire response. Finally, the division of agricultural lands into smaller parcels with the development of new residential areas complicates access for fire responders and increases the probabilities of human-caused ignitions.

Contributing Factors: Climate

Climate is a central determinant of wildfire occurrence and behavior (Krawchuk et al. 2009) and climate change has been linked to regionally specific increases in fire activity (Moritz et al. 2012). Fuel accumulation and fuel moisture are driven by precipitation, temperature, and humidity over short to medium time scales, whereas wind speed and direction strongly influence fire intensity and the direction and rate of spread at the time of fire occurrence. Hawai'i experiences a wide range of climate conditions over relatively small spatial scales because of the islands' steep and complex topography, dominant northeasterly trade wind-driven weather patterns, and associated orographic precipitation patterns. Evidence suggests these conditions have remained relatively constant, with cyclical increases in precipitation tied to decreased sea level during glacial periods over millennial

time scales (Gavenda 1992, Sheldon 2006) and to "cool" phases of the Pacific Decadal Oscillation on shorter time scales (Frazier et al. 2012). However, within the past century, there is strong evidence for both decreasing rainfall (Frazier et al. 2011, Chen and Chu 2014, Kruk et al. 2014, Elison Timm et al. 2015) and increasing temperature (Giambelluca et al. 2008). The fire history data demonstrate an increase in annual area burned and ignitions during the warmer, drier conditions that prevail during summer months (June–August) (Figure 3). In terms of interannual variability, larger fires have been previously correlated to drought conditions in Hawai'i (Dolling et al. 2005, Cram et al. 2013), while Chu et al. (2002) found a significant increase in area burned in the summers following El Niño events. These patterns suggest that wildfire occurrence may continue to increase across the state with future warming and drying, yet explicitly linking climate trends to past changes in wildfire occurrence in Hawai'i is difficult due to the contemporaneous increases in both human population and activity (i.e., ignitions) and the flammability of vegetation (i.e., nonnative grass expansion) across Hawai'i's landscapes over the past century.

Ecological and Societal Impacts

The contemporary wildfire regime in Hawai'i affects natural and cultural resources on all islands, with implications for human health and safety as well as economic development. Wildfire is a major cause of habitat degradation and native species decline in Hawai'i (see review by LaRosa et al. 2008) and the potential for wildfire to cause species extinctions is far greater in Hawai'i than in continental regions. The state contains 41% of the 845 federally listed threatened and endangered plant species, of which >50% are restricted to three or fewer populations (U.S. Fish and Wildlife Service, unpubl. data), making them extremely vulnerable to a single wildfire. Wildfire's complex interactions with nonnative plants and animals also pose unique challenges. The status quo approach to conservation of biological diversity in Hawai'i is to fence areas and remove nonnative ungu-

lates, such as feral sheep, goats, pigs, and cattle, because these animals reduce native plant cover, regeneration, and survival (Mueller-Dombois and Spatz 1975, Cole and Litton 2014, Murphy et al. 2014). However, removing grazing animals may also release nonnative plants (Kellner et al. 2011, Cole and Litton 2014) and could increase fine fuel loads and thus fire intensity (e.g., inferred from greater flame lengths and rates of spread) when wildfires occur (Blackmore and Vitousek 2000). Ungulate removal is critical for native habitat conservation; however, the trade-offs with wildfire risk need to also be assessed, especially in drier ecosystems (e.g., Scowcroft and Conrad 1992, Thaxton and Jacobi 2009), to determine when and where fuels reduction measures are also required.

In addition to the direct threat posed to native species, wildfire can have negative impacts on critical ecosystem services that directly affect the quality of life for Hawai'i's residents and visitors. The loss of vegetation immediately following wildfire has been found to greatly increase soil erosion (Ice et al. 2004) and the amount of sediment carried into streams and other water resources downslope in temperate ecosystems (Neary et al. 2003). In the Pacific, erosion from grasslands on Guam increased sixfold immediately after burning and remained twice that of unburned grasslands up to 18 months following wildfire (Minton 2006). Over the longer term, reductions in woody plant cover due to repeated wildfires can decrease water table depth and infiltration into the soil, both of which can dramatically increase discharge volumes and peak stormflow, and hence downstream flooding and sedimentation during rainfall events (Le Maitre et al. 1999). Postfire impacts on landscape aesthetics have serious potential implications for Hawai'i's tourism industry, whereas sediment loading in near-shore coral reef ecosystems threatens critical biodiversity, food, and recreational resources for residents and visitors (Minton 2006, DOFAW 2010). Burned areas in Hawai'i remain closed to the public for days to months (e.g., state lands following the 2007 Polipoli fire on Maui and the 2012 Hikimoe Ridge fire on Kauai) due to landslide and tree-fall danger, thereby limit-

ing access for hiking, hunting, gathering plants, and tending of cultural sites. Frequent fires in developed areas also impact power and communication infrastructure and lead to road closures and other municipal challenges (Figure 4). Despite the spatial extent and diversity of resources currently affected by wildfire in Hawai'i, there has been little integration of wildfire risk and impacts into assessments of ecosystem services, community planning, disaster preparedness, or climate change mitigation.

Prevention and Management of Wildfire in Hawai'i

The risks and impacts of wildfire can be reduced through expanded prevention, more prefire management to improve the effectiveness of fire suppression, and enhanced post-fire response. Given that nearly all wildfires in Hawai'i are human-caused, outreach and education are critical in Hawai'i and local programs, including DOFAW and HWMO, have already adapted national resources such as Ready, Set, Go!, and Firewise Communities to local contexts (e.g., <http://hawaiiwildfire.org/ready-set-go2.html>). Directly reducing wildfire risk requires managing vegetation to reduce the quantity and continuity of available fuels, which has been shown to reduce costs and increase effectiveness of fire suppression elsewhere (Hurteau and North 2009, Syphard et al. 2011). However, evidence for the benefits of fuels management is limited in Hawai'i (e.g., Beavers et al. 1999, Castillo et al. 2003, Ansari et al. 2008). Traditional fuel breaks in which vegetation is reduced or eliminated by mechanical and/or chemical means can disrupt fuel continuity and provide firefighters with access and defensible space, but are costly to maintain in Hawai'i given the islands' difficult terrain and rapid rates of year-round plant regrowth, especially in nonnative grasslands (D'Antonio and Vitousek 1992).

These challenges have raised a call among Hawai'i's fire management community for cost-effective, alternative fuels management strategies (PacificFireExchange.org). Grazing has been prescribed to reduce fuels in grassland areas of Hawai'i, although the trade-offs

between wildfire risk reduction and long-term forage sustainability are not well quantified (M. Thorne, pers. comm.). Still, grazing has been shown to effectively reduce fine fuel loads through field assessments (Blackmore and Vitousek 2000), experimental prescriptive trials (Castillo et al. 2003, Ansari et al. 2008), and remote sensing (Elmore et al. 2005). Another alternative is vegetated fuel breaks, or “greenstrips,” that integrate fire-resistant shrubs and grasses (St. John and Ogle 2009) and/or use trees to reduce herbaceous fuels via shading (e.g., Trauernicht et al. 2012). However, plant species suitability and the effectiveness of greenstrip implementation in Hawai‘i is only beginning to be quantified (Ellsworth 2012).

Postfire needs for soil stabilization and longer term revegetation have resulted in investments to increase seed storage capacity through both regional efforts such as the Hawai‘i Island Native Seed Bank Cooperative and site-based projects such as the Pu‘u Kukui Watershed Preserve on Maui (P. Kaniaupio-Crozier, pers. comm.). There is also increasing discussion among the management community about taking advantage of postfire conditions to increase native species restoration and landscape resilience to future fires (e.g., Loh et al. 2009). Scaling up the capacity for ecological restoration, reforestation, and watershed management more generally can also inform postfire strategies. The Auwahi Dry Forest on Maui has excluded fire-prone nonnative grasses on the order of hectares, albeit through highly intensive weeding and planting of native trees and shrubs (Medeiros et al. 2014). Larger-scale reforestation projects, such as those at Hawai‘i Volcanoes National Park and Hakalau Forest National Wildlife Refuge on Hawai‘i Island and the Kula Forest Reserve following the 2007 Polipoli fire on Maui, have targeted tens to hundreds of hectares (R. Loh, A. Kikuta, and L. DeSilva, pers. comm.). Reducing fire risk, however, is more complex than simply ramping up restoration efforts. For example, high planting density and canopy closure are critical to reducing fine fuel loads (McDaniel and Ostertag 2010, R. Loh, pers. comm.). Native plants used in restoration also vary in

their ability to recover from future fires (Ainsworth and Kauffman 2009, Loh et al. 2009, Ammond and Litton 2013), as well as their propensity to burn. The commonly used shrub species *Dodonaea viscosa* (L.) Jacq., for instance, is extensively planted at dry forest sites but has been found to have extremely low live fuel moisture (Ellsworth 2012). Ultimately, many ecological restoration sites and critical watersheds in fire-prone areas of Hawai‘i will continue to depend on “traditional” strategies such as fuel breaks and ongoing cooperation with fire response agencies to protect these areas from wildfire.

Fire Suppression Challenges

Wildfires in Hawai‘i’s nonnative grasslands create difficult and dangerous conditions for fire suppression personnel. Rates of spread can be rapid and fire intensities high (W. Ching and M. Nakahara, pers. comm.) because of very high fine fuel loads (Beavers et al. 1999, Castillo et al. 2003, Ellsworth et al. 2013). Furthermore, Hawai‘i’s rugged terrain provides few options for safe ingress/egress, often limiting suppression efforts at a fire’s leading edge to water drops from helicopters, which substantially increases suppression costs. Wildfire response jurisdictions in Hawai‘i are split among various agencies, many of which maintain mutual aid agreements to share resources. The four county fire departments (Hawai‘i, Kaua‘i, and Maui Counties, and the City and County of Honolulu on O‘ahu) provide initial response to the majority of wildfires in the state, but they are primarily trained and equipped for structural fires. The Hawai‘i Division of Forestry and Wildlife is the primary fire response agency for wildfires on state lands (41% of state land area; >640,000 ha) and often assists county fire departments. However, DOFAW employs no full-time firefighters, acting instead as a reserve or militia-style response agency. Federal agencies fund the only full-time wildfire suppression programs in the state at Hawai‘i Volcanoes National Park and the U.S. Army garrisons on Hawai‘i and O‘ahu Islands. Importantly, Hawai‘i’s geography also prevents the rapid mobilization of heavy equipment such as

water trucks, brush trucks, and dozers among islands, although personnel are typically mobilized in the event of large wildfires.

Future Directions

A significant challenge facing fire management in Hawai'i is the lack of science-based, regionally relevant information that is accessible to land managers and fire responders (PacificFireExchange.org). Our understanding of wildfire dynamics in Hawai'i, and on tropical islands more generally, is limited relative to the development of fire research and management knowledge in continental ecosystems. For instance, established tools for fire prediction and operational response, such as standard fuel and fire spread models and the National Fire Danger Rating System, have uncertain applicability in Hawai'i due to high environmental variability, completely novel fuel types, limited weather data, and limited opportunities to conduct experimental burns (Beavers et al. 1999, Fujioka et al. 2000, Benoit et al. 2009, Weise et al. 2010, Ellsworth et al. 2013). Given the existing knowledge gaps and limited resources for projects, it is imperative that efforts to further develop fire science in Hawai'i explicitly meet the needs of and be made accessible to on-the-ground practitioners. To that end, in 2011 the U.S. Department of Agriculture Forest Service partnered with the nonprofit group Hawai'i Wildfire Management Organization, and the College of Tropical Agriculture and Human Resources of the University of Hawai'i at Mānoa to create the Pacific Fire Exchange (PacificFireExchange.org), a member of the national Joint Fire Science Program's Fire Science Exchange Network (www.firescience.gov). The purpose of the Pacific Fire Exchange is to improve communication between the science and practitioner communities in Hawai'i and U.S. Affiliated Pacific Islands by increasing collaboration and developing and disseminating science-based, best practices for fire management based on stakeholder needs.

Due to the scale of Hawai'i's fire-prone ecosystems, the complexity of factors driving wildfire occurrence, and limited available re-

sources, partner-driven and collaborative approaches will be critical to improving fire management. Partnerships such as the Big Island Wildfire Coordinating Group, the West Maui Fire Task Force, and the Oahu Wildfire Information and Education Group provide excellent examples of cooperation among fire response agencies. The key resources impacted by wildfire, such as freshwater provisioning, native forest habitat, and nearshore ecosystems, also indicate that fire management goals are directly aligned with objectives identified by land and watershed managers more broadly (e.g., DOFAW 2010). This provides opportunities to link wildfire-focused partnerships with existing collaborative land management efforts such as the Hawai'i Association of Watershed Partnerships to expand the scale and impact of wildfire preparedness and mitigation efforts. The explicit relationship between wildfire and human activity in Hawai'i (Figures 4 and 5) also strongly suggests that reducing wildfire impacts will require bridging the ecological dimensions of land management with social issues such as human behavior, public safety, education, economics, and disaster response. HWMO has played a pivotal role in this area through on-the-ground wildfire education and the facilitation of Community Wildfire Protection Plans across the state. These efforts have brought together the interests and expertise of fire responders, large land managers, and the general public and provided impetus for collaborative, community-based wildfire mitigation projects. Additional opportunities to address and better understand the human dimensions of wildfire in Hawai'i include collaborations with place-based education programs that foster environmental and cultural stewardship, and projects that address landscape-scale issues of land development and planning.

CONCLUSIONS

Increases in wildfire occurrence in Hawai'i (Figure 2) are likely to continue given a growing human population, expanding invasive grass cover, and projected temperature increases and precipitation declines (Giambelluca

et al. 2008, Frazier et al. 2011, Elison Timm et al. 2015). Wildfire threatens human communities and a multitude of natural and cultural resources. There are formidable challenges facing fire management today and into the future in Hawai'i. However, awareness of Hawai'i's wildfire problem is spreading from those directly involved with fire response into the wider land management community, policy makers, and the general public. Due to its disregard for property lines and the diversity of resources it affects, wildfire provides an immediate and explicit incentive to bring fire responders, land managers, researchers, and local communities together to promote the protection of valued natural and cultural resources.

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