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Using a prescribed fire to test custom and standard fuel models for fire behaviour prediction in a non-native, grass-invaded tropical dry shrubland

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Nomenclature
Wagner et al. (1999)

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Abstract

Questions: Do fuel models developed for North American fuel types accurately represent fuel beds found in non-native, grass-invaded tropical dry shrublands? Do standard or custom fuel models used in fire behaviour models with *in situ* or remote automated weather stations (RAWS) measured fuel moistures affect the accuracy of predicted fire behaviour in grass-invaded tropical shrublands?

Location: Hawai'i Volcanoes National Park, Hawai'i, USA.

Methods: Pre-fire fuel loads of coarse woody debris, live herbaceous and live woody fuel loads were quantified with Brown's transects and biomass sampling to create a custom fuel model for non-native grass-invaded tropical dry shrublands in Hawai'i. *In situ* fuel moistures were quantified using oven-dried vegetation samples, and compared to RAWS estimated fuel moistures. Fire behaviour was recorded on a stationary video camera to quantify flame length (FL) and rate of spread (ROS). Observed fire behaviour was compared to BehavePlus predicted fire behaviour parameterized with both standard and customized fuel models, and *in situ* and RAWS-based estimates of fuel moisture.

Results: The custom fuel model and measured fuel moistures performed better than most standard models, but over-predicted actual ROS and top decile FL by 29% and 26%, respectively. The best match between observed and modelled fire behaviour came from a standard fuel model for shrublands with a grassy matrix (23% under-prediction for ROS and 9% under-prediction for FL) using measured fuel moistures. Using fuel moistures and wind speeds estimated from the nearest RAWS station (5 km from the fire) substantially decreased prediction accuracy of the custom fuel model and increased its relative error to 71% over-prediction of ROS and 45% over-prediction of FL.

Conclusions: Fire behaviour in at least some tropical fuel beds can be accurately modelled using certain standard or custom fuel models. Standard fuel models should not be applied uncritically to systems outside of North America, as our comparison showed widely ranging accuracy across six standard models. In addition, the current reliance on RAWS data for meteorological inputs to predict fire behaviour in the tropics, especially in the US-affiliated tropical Pacific, must be used with caution. Instead, field-measured fuel moistures should be used when possible.

Introduction

Tropical wildfires are the most important but least studied component of the global fire regime (Cochrane 2009a; Krawchuk et al. 2009). In particular, the invasive grass–fire cycle has the potential to completely restructure vegetation communities and ecological processes in tropical forest ecosystems (Hughes et al. 1991; D'Antonio & Vitousek 1992; Mack et al. 2001; Cochrane 2009a; D'Antonio et al. 2011). While tropical wildfires affect large areas of land

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and are important to the global carbon cycle, they are vastly under-studied compared with temperate and boreal wildfires. In particular, fire behaviour in invasive grass-dominated tropical ecosystems has received remarkably little scientific attention (Kauffman et al. 1994; Mistry 1998; Ellsworth et al. 2013; see Beavers 2001), and this knowledge gap compromises fire management efforts directed at the conservation of native dry and mesic forest ecosystems (Blackmore & Vitousek 2000; Cabin et al. 2000; Pau et al. 2009). Notably, fire is a long-term, albeit historically infrequent, disturbance agent in Hawai'i that has changed radically in the past century with human activities (Kirch 1982; Smith & Tunison 1992), including in the coastal lowland areas of Hawai'i Volcanoes National Park (HVNP; HVNP cultural resources, unpubl. data). Today, fires on Pacific islands often promote non-native grass invasions that can suppress or kill native plants through promotion of a grass–fire cycle, increased competition for resources, and altered resource supply and micro-climate conditions (Mack et al. 2001; Ainsworth & Kauffman 2010).

As in other areas of the tropics, it is likely that non-native grass-driven fires have become a permanent part of the Hawaiian landscape (D'Antonio & Vitousek 1992; Rossiter et al. 2003; Ainsworth & Kauffman 2010). Fire behaviour studies in other regions have shown that fires in ecosystems dominated by invasive grasses can be more intense and potentially more damaging than fires burning in native fuels (Rossiter et al. 2003; Setterfield et al. 2010). As a result, there is growing interest in fire management to decrease the impacts of fires in non-native grasslands (Daehler & Goergen 2005; Castillo et al. 2007). However, key questions about fuel properties and fire behaviour in grass-invaded tropical ecosystems remain an impediment to predicting and managing wildfires. Given the enormous land area in the tropics affected by fire – 27.6 million km^2 of savanna alone (Hutley & Setterfield 2008) – surprisingly few fuel models have been developed for the widely ranging vegetation types supporting fire regimes. In Hawai'i, this knowledge gap undermines confidence in the utility of the standard fuel models needed to parameterize and run fire behaviour models.

In Hawai'i, scientific studies of fire behaviour and fuel loads have not always treated fire and fuels comprehensively (Blackmore & Vitousek 2000; Beavers 2001; Wright et al. 2002; Castillo et al. 2007). Physical properties of some invasive grasses in Hawai'i have been quantified, including *Melinis minutiflora* (Fujioka & Fujii 1980) and *Megathrysus maximus* (Beavers 2001; Ellsworth et al. 2013), but in general the information needed to inform wildfire management is conspicuously lacking. Beavers (2001) developed a custom fuel model for an invasive *M. maximus*-dominated grassland on O'ahu by quantifying both fuel loads and observed fire behaviour. He determined that this grass has the potential to burn with extreme behaviour, including flame lengths up to 10 m, and that standard fuel models were not appropriate for the fuel bed associated with this species. Furthermore, while it is standard practice to measure total fuel loads on a mass per unit area basis in the field (e.g. Wright et al. 2002; NPS 2003), differences between fire behaviour model default values and field-measured values of physical fuel parameters, such as intrinsic heat content (Reid & Robertson 2012) and surface area to volume ratio (Fujioka & Fujii 1980), can alter fire behaviour predictions (Reid & Robertson 2012). These knowledge gaps leave natural resource personnel tasked with wildfire management, but lacking the basic information, data and expertise needed to assess standard fuel models and fire behaviour modelling software. Therefore, managers need guidance on whether and how much to utilize standard fuel models compared to labour-intensive, custom approaches.

In addition to appropriate fuel models required by fire modelling software, fire weather and fuel moisture variables are critical for accurately predicting fire behaviour. In the coterminous US, these variables are typically derived from RAWS stations and are generally accepted as part of the National Fire Danger Rating System (NFDRS). Weise et al. (2005), however, showed that RAWS reported fuel moistures for many Hawaiian sites did not accurately predict field-measured fuel moistures, potentially as a result of the year-round growing conditions in the tropics. Therefore, fuel moistures reported by RAWS in Hawaiian locations must be critically examined to determine their applicability to fire behaviour predictions.

Finally, comparisons of observed fire behaviour vs predicted behaviour require that observations be made under conditions that fulfill the assumptions under which the fire behaviour modelling program was built. On the other hand, observing wildfires can be difficult and dangerous due to their unpredictable nature, which results in the common practice of making *post-hoc* observations of fire effects to infer fire behaviour (e.g. Hall & Burke 2006; Knapp & Keeley 2006), with largely unknown consequences.

In this study, we took advantage of a 2011 prescribed fire that was allowed to burn as a free-running head fire in a 42-ha vegetation patch completely surrounded by barren lava. These conditions allowed for a close, safe vantage point from which fire behaviour could be observed and allowed subsequent comparison to predictions from a commonly used fire behaviour prediction software. The objectives of this study were to: (1) quantify fuel loads in a grass-invaded tropical dry shrubland; (2) observe and document characteristics of a free-burning fire in this ecosystem type; (3) compare custom fuel loads and fuel moisture contents to standard fuel models and RAWS-derived fuel moisture; and (4) evaluate the potential utility of standard and custom fuel models for accurate fire behaviour prediction.

Methods

Study area

Hawai'i Volcanoes National Park (HVNP) lies on the southeastern flank of Hawai'i Island, the largest and southeastern-most island in the Hawaiian archipelago (Fig. 1). The prescribed fire took place in the 42-ha Kipuka Kealakomo Waena (kipuka is the Hawaiian term for a forest fragment on older substrate isolated by a more recent lava flow), located in the coastal lowlands (60–150 m·a.s.l.) at ca. 19°17′30″N, 155°9′15″W. The substrate is 1500–3000-yr-old pāhoehoe lava – smooth-surfaced lava with an often ropy appearance – with a thin (0–18 cm) basaltic ash-derived, somewhat excessively drained soil with limited water-holding capacity (NRCS 2012). The kipuka was isolated from surrounding forest during the 1972 Mauna Ulu flows from Kilauea (Sherrod et al. 2007). This area receives an average annual rainfall of 1371 mm (HVNP fire management unpubl. data, Pu'u loa rain gauge 1988–2008) with high inter-annual variation. The majority of precipitation occurs during the winter months. Temperature seasonality is low, and the diurnal range of 5–8 °C is larger than the difference between summer and winter average highs (30 vs 26 °C, respectively; WRCC 2012).

As a result of two previous prescribed fires in the study area (1999, 2009), most fire-sensitive species are absent from this kipuka. Before the 2011 prescribed fire, the study area was dominated by the post-European contact invasive C_4 grasses *Melinis repens* and *M. minutiflora*, with small patches dominated by native *Heteropogon contortus*. There was also a scattered woody component consisting of the native shrubs *Dodonaea viscosa* and *Tephrosia purpurea* and the native sub-shrub *Waltheria indica*.

Fuel bed characteristics

Vegetation cover was estimated along 24 randomly placed 30-m transects using a modified pole (1-cm diameter, 2-m height) intercept method. Each transect was read at 30-cm intervals for a total of 100 points per transect. All plant species in contact with the pole at each point were recorded once, which results in up to 100% cover per species and >100% cover for species groupings. Dead vegetation attached to live vegetation was counted as live vegetation for establishing vegetative cover only (as in Tunison et al. 2001). Substrate (soil, litter, rock) was recorded only when no plant species were in contact with the pole.

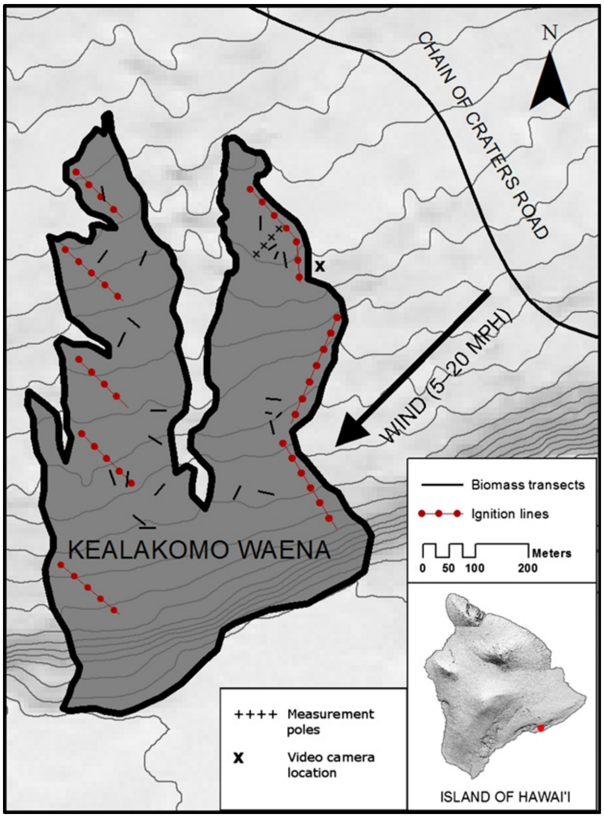

Fig. 1. Map of Kipuka Kealakomo Waena. Note that the locations of the measurement poles and video camera are approximate, as well as the track of the fire ignition line, and symbols are enlarged for clarity.

Biomass transects for measuring fuel loads were established in dominant *H. contortus*, *M. repens* and *M. minutiflora* areas (n = 22). Fuel samples were collected in three subplots located 2–3 m off the transect line at 2-, 7- and 12-m intervals along each 30-m transect. No rejection criteria were used. All vegetation within a 25 cm × 25-cm plot was clipped at 1 cm above the ground surface, divided by species, dried at 100 °C for 72 hr and weighed. Woody fuel accumulation and the depth of litter and duff were measured along 48 Brown's fuel transects originating from a subset of the cover transects. Fuel transects started at 0, 10, 20 and 30 m along each cover transect at random azimuths. Fuel lines were not rejected if they intersected each other. We used National Park Service standard protocols for tallying fuels along transects (NPS 2003). We used FMA Plus© (FPS 2005) to convert coarse woody fuel counts into tons per acre loading, and then converted to Mg·ha^{-1}.

Fuel models

A custom fuel model was constructed to conform to BehavePlus 5.0 standard inputs (Andrews 2009) based on field measurements to represent fuel conditions at the time of the 2011 prescribed fire. Field observations were used to estimate: (1) 1-, 10-, 100-hr, live herbaceous and live woody fuel loads; (2) 1-, 10-hr, live herbaceous and live woody fuel moistures; (3) mid-flame wind speed and direction; and (4) slope angle and aspect. For herbaceous fuels, we used published estimates of live herbaceous surface area to volume (SA/V) and fuel bed height for *M. minutifolia* from Fujioka & Fujii (1980). Lastly, we used the standard values from Fuel Model 3 (Albini 1976; Anderson 1982) for 1-hr SA/V, Live Woody SA/V, dead fuel moisture of extinction, and Live and Dead fuel heat content. To assess similarity between fuel models, we calculated the Euclidean distance in parameter space between the custom fuel model and the standard fuel models for each fuel loading parameter (1-, 10, 100-hr, live herbaceous and live woody) and fuel bed depth.

Fuel moisture content (FMC) for 1-, 10-hr, live herbaceous and live woody fuels was measured on 158 samples taken between 12:00 and 13:00 hr 1 d prior to the 2011 prescribed fire. We quantified FMC for *D. viscosa*, *M. minutiflora*, *M. repens*, *Pluchea symphytifolia*, *Indigofera suffruticosa*, *Lantana camara* and 1- and 10-hr coarse woody debris. We took 20 samples from each of the above fuel categories and species and placed them in clear plastic containers with snap-tight lids. Each sample was weighed that same day and its wet weight (WW) recorded. All the samples were then dried at 70 °C for 1 wk to a constant weight (Agee 1983; Bradstock & Gill 1993) and its FMC calculated. We further grouped FMCs to support fire behaviour modelling in the BehavePlus fire behaviour modelling environment in the following categories: 1-, 10-hr, live woody and live herbaceous fuels. We estimated live woody FMCs using a cover-weighted average of *I. suffruticosa*, *D. viscosa*, *P. symphytifolia* and *L. camara* values. We estimated live herbaceous FMCs using a cover-weighted average of *M. minutiflora* and *M. repens* values.

Fire behaviour observations

We erected four 3.1-m long steel poles painted in alternating black and white 30-cm increments in the eastern arm of the kipuka, and spaced at 10-m intervals in a straight transect along the anticipated direction of maximum fire spread. We set a video camera on a tripod to record the passage of the flaming front following drip-torch ignition (Fig. 1). We derived estimates of flame length (FL) and rate of spread (ROS) from video observations. First, we estimated flame heights and flame angles at 5-s intervals by comparing heights to the nearest measurement pole and measured flame angle above horizontal using a compass with a built in clinometer. Flame heights and angles were converted to FL using trigonometric relationships. We quantified average FL, average maximum FL and 90th percentile FL from the raw FL data. The ROS was calculated by noting the time at which the flaming front reached each measurement pole. Fire ignition for the section covered by video was provided by NPS fire personnel from the Whiskeytown Fire Use Module starting at 10:11 hr. The fire was lit such that it would spread in the direction of the prevailing winds and produce as much free-running head fire as possible. Fire activity ended by 11:00 hr.

Fire behaviour modelling

We used the BehavePlus 5 fire modelling program (Heinsch & Andrews 2010) to calculate FL and ROS using either our custom fuel model or one of six standard fuel models [GR3, GR4, GR5, GR7, GS3 (Scott & Burgan 2005) and Fuel Model 3 (Albini 1976; Anderson 1982)]. Models GR3, GR4, GR5 and GR7 represent grass-dominated fuel beds with increasingly larger loads in the 1-hr and herbaceous categories. Model GS3 also includes a significant shrub component. Fuel Model 3 represents a fuel bed composed completely of 1-hr fuels (Albini 1976). Fuel model selection was based on Scott & Burgan (2005).

Fuel moistures and fire weather conditions were obtained from two sources. First, we used fuel moistures, wind speed and direction observed *in situ* immediately before the burn. Second, we used the fuel moisture and wind data reported by the nearest RAWS (Kealakomo, station ID: 328074; WRCC 2012), which is located <5 km east of the study site in the same ecosystem type.

We constructed a simple sensitivity analysis to examine how the standard and custom fuel models responded to changes in fuel moistures and wind speeds. A sensitivity analysis such as this gives fire managers useful context for the analysis of a fuel model or of prescribed fire behaviour by elucidating potential threshold effects in the model predictions of fire behaviour (Jolly 2007), and how their own fire prescriptions or fire attack plans may change with changing conditions during a fire. We set up a factorial design to deal with changes in fuel moisture and wind speed that would be most likely to change the results or to affect fire behaviour in the field. We systematically assessed potential error source by varying the observed fuel moisture and wind speed independently by ±25% and ±10% and calculated ROS and FL for comparison to observed fire behaviour. Finally, we measured similarity between the observed and predicted ROS and FL for the observed data and the predicted data by calculated distance in parameter space (analogous to RMSE).

Results

Vegetation cover

Non-native species cover dominated the burn area before the fire, with *M. repens* and *M. minutiflora* having the highest absolute cover at 60% and 21%, respectively (Table 1). The native woody species *W. indica* had the highest cover of any native plant at 22%. *Heteropogon contortus*, a native grass, had a low overall cover (7%). Non-native plants accounted for 105% of total cover compared to just 35% cover for native plants and 11% cover as bare substrate.

Fuel bed characteristics and burning conditions

The fuel bed was dominated by live herbaceous (mean = 5.7 ± 1.69 Mg·ha^{-1}; ±SE) and live woody (mean = 2.6 ± 0.79 Mg·ha^{-1}) components, but each was highly variable, with some samples near zero and one herbaceous sample of 17.8 Mg·ha^{-1} (Fig. 2). *Melinis repens* had the highest average fuel load (2.6 ± 0.5 Mg·ha^{-1}), while *H. contortus* had the second highest average fuel load of all live vegetation (2.3 ± 0.65 Mg·ha^{-1}; Table 2). Overall, live fuel loading in the study area averaged 8.3 ± 0.44 Mg·ha^{-1}. There was an additional 4.0 ± 0.32 Mg·ha^{-1} in dead woody and litter biomass. The 1-hr dead fuels averaged 0.47 ± 0.04 Mg·ha^{-1} (Table 3) and exhibited a small range while 10-hr dead fuels averaged 3.11 ± 0.39 Mg·ha^{-1} and had a much larger range of up to 8.85 Mg·ha^{-1}. The average load of 100-hr dead fuels was very low (0.11 ± 0.08 Mg·ha^{-1}), as 100-hr fuels were rare and appeared on only two transects where they contributed 1.21 Mg·ha^{-1} to each transect. The custom fuel model was most similar to standard model

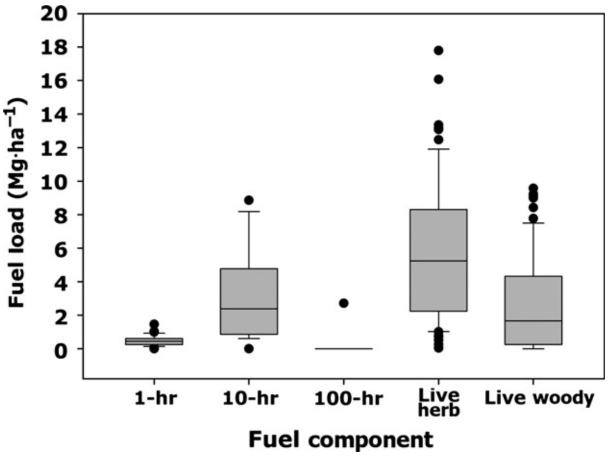

Fig. 2. Box-plot of measured fuel loads. Measured fuel loads of coarse woody fuel transects (1-, 10- and 100-hr fuels; *n* = 48) and biomass quadrats (live herbaceous and live woody fuels; *n* = 66).

Table 1. Average percentage cover of live species. Non-native or native status and herbaceous–woody classification conducted by HVNP Natural Resources staff. Substrates (dead grass, rock, litter or soil) were only recorded if no live vegetation contacted the sampling pole. See text for full details.

Status	Form	Full Name	% Cover	SE
Alien	Herb	*Bulbostylis capillaris*	0.42	0.24
	Herb	*Desmodium triflorum*	1.83	0.72
	Herb	*Melinis minutiflora*	20.79	2.60
	Herb	*Melinis repens*	59.63	3.78
	Herb	*Passiflora foetida*	1.08	0.71
	Woody	*Chamaecrista nictitans*	9.75	1.29
	Woody	*Crotalaria pallida*	1.25	0.49
	Woody	*Indigofera suffruticosa*	9.75	2.24
	Woody	*Lantana camara*	0.46	0.20
	Woody	*Pluchea symphytifolia*	0.42	0.23
		Total alien	105.38	4.45
Native	Herb	*Heteropogon contortus*	6.71	2.36
	Herb	*Ipomoea indica*	6.50	0.94
	Woody	*Tephrosia purpurea*	0.04	0.04
	Woody	*Waltheria indica*	21.58	1.82
		Total native	34.83	2.84
		Dead grass	1.25	0.28
		Rock	7.00	0.59
		Litter	1.83	0.38
		Soil	1.38	0.26
		Total substrate	11.46	0.83

Table 2. Average biomass of live vegetation and dead components. The data were collected from the biomass transects.

Status	Form	Full Name	Mg·ha^{-1}	SE
Alien-Live	Herb	*Bulbostylis capillaris*	<0.01	<0.01
	Herb	*Desmodium triflorum*	0.01	<0.01
	Herb	*Melinis minutiflora*	0.51	0.17
	Herb	*Melinis repens*	2.64	0.50
	Herb	*Passiflora foetida*	0.18	0.16
	Woody	*Chamaecrista nictitans*	0.36	0.09
	Woody	*Crotalaria pallida*	0.14	0.08
	Woody	*Indigofera suffruticosa*	0.65	0.22
	Woody	*Lantana camara*	0.0	0.0
	Woody	*Pluchea symphytifolia*	0.0	0.0
		Total live alien	4.48	0.58
Native-Live	Herb	*Heteropogon contortus*	2.27	0.65
	Herb	*Ipomoea indica*	0.10	0.02
	Woody	*Tephrosia purpurea*	0.0	0.0
	Woody	*Waltheria indica*	1.46	0.27
		Total live native	3.83	0.57
Dead Material	Woody	<0.64 cm	0.54	0.13
	Woody	0.64–2.54 cm	0.31	0.10
	Litter	Litter	3.20	0.23
		Total live	8.31	0.44
		Total live herbaceous	5.70	1.69
		Total live woody	2.61	0.79
		Total dead	4.05	0.32

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Table 3. Comparison of the custom and standard fuel model values. Fuel model 3 is from Albini (1976). Fuel models GR3, GR4, GR5, GR7 and GS3 are from Scott & Burgan (2005).

Model parameter	Fuel model name						
	Custom	3	GR3	GR4	GR5	GR7	GS3
Fuel model type	Dynamic[b]	Static	Dynamic	Dynamic	Dynamic	Dynamic	Dynamic
1-hr fuel load (Mg·ha^{-1})	0.47[a]	6.75	0.22	0.56	0.9	2.24	0.67
10-hr fuel load (Mg·ha^{-1})	3.12[a]	0	0.9	0	0	0	0.56
100-hr fuel load (Mg·ha^{-1})	0.11[a]	0	0	0	0	0	0
Live herbaceous fuel load (Mg·ha^{-1})	5.7[a]	0	3.36	4.26	5.6	12.1	3.25
Live woody fuel load (Mg·ha^{-1})	2.6[a]	0	0	0	0	0	2.8
1-hr SA/V (m^{2}·m^{-3})	4921[b]	4921	4921	6561	5905	6561	5905
Live herbaceous SA/V (m^{2}·m^{-3})	6604[c]	4921	4265	5905	5249	5905	5249
Live woody SA/V (m^{2}·m^{-3})	4921[b]	4921	4921	4921	4921	4921	5249
Fuel bed depth (m)	0.67[c]	0.76	0.61	0.61	0.46	0.91	0.55
Dead fuel moisture of extinction (%)	25[d]	25	30	15	40	15	40
Dead fuel heat content (kJ·kg^{-1})	18622[d]	18622	18622	18622	18622	18622	18622
Live fuel heat content (kJ·kg^{-1})	18622[d]	18622	18622	18622	18622	18622	18622
Distance between custom and standard models in euclidean parameter space (unitless)	–	9.40	4.16	4.31	4.08	7.79	3.55
Distance between predicted fire behaviour and observed (unitless)	0.572	3.711	0.453	2.692	3.294	8.758	0.457

The source of the values for the custom fuel model are [a]this study; [b]Scott & Burgan (2005); [c]Fujioka & Fujii (1980); [d]Albini (1976). For differences between models in Euclidean space, see the text.

GS3 based on Euclidean distance in parameter space (Table 3).

Fuel moisture ranged from 8% for 1-hr dead woody fuels to 297% for live *P. symphytifolia*. In general, the highest fuel moistures were in live woody species (*P. symphytifolia*, *I. suffruticosa*, *L. camara* and *D. viscosa*). The lowest fuel moistures were found in 1-hr (8.00 ± 0.01%) and 10-hr (9.00 ± 0.01%) dead woody fuels. *Melinis minutiflora* (49.00 ± 0.07%) and *M. repens* (26.00 ± 0.03%), two non-native grasses, had the lowest live fuel moistures of any species sampled. Live woody fuel moistures averaged 251% (±0.10) and live herbaceous moistures averaged 32% (±0.04). We did not sample fuel moisture for any 100-hr fuels because of their rarity on the landscape, so we used a value of 10% for the 100-hr fuel moisture in our fire behaviour modelling (1% higher than the 10-hr moisture). Fuel moistures from the nearest RAWS station were 14% for 1- and 10-hr fuels, 16% for 100-hr fuels, 30% for live herbaceous fuels and 114% for live woody fuels.

Wind speeds were estimated on site as varying between 7 and 32 km·h^{-1}, blowing from the north and northeast (N. DeWeese, internal fire behaviour report), which corresponds to the direction in which the measurement poles were placed (NNE to SSW). Wind speed reported by the closest RAWS was 24 km·h^{-1} blowing from 54°.

Fire behaviour and model comparisons

The maximum observed FL was 4.41 m, the average maximum FL was 2.17 ± 0.15 m and average FL was 1.19 ± 0.05 m (Table 4). Because fire modelling software produces estimates for use in predicting the difficulty of fire control, we also chose to analyse the top decile of FL (Andrews 2009). Thus, we also computed the bootstrapped average of the top 10% of observations of maximum FL (90th percentile and higher). The average of the top 10% of observations was 3.73 ± 0.21 m. Flame angles were moderate to steep and ranged from 38° to 86° above horizontal. Observed ROS values ranged from 0.33 to 0.91 m·s^{-1}, with an average of 0.57 ± 0.14 m·s^{-1} (1.9 km·h^{-1}).

All fuel models used with observed weather and fuel moistures consistently over-predicted average FL and average maximum FL, but over-predictions ranged from trivial to enormous. In contrast, the top decile maximum FL was under-predicted by 9% using model GS3, representing an open shrubland with a grassy matrix, and within 4% by model GR3, representing a grassland with a fuel depth of 30–60 cm (Fig. 3). However, the remaining four standard fuel models over-predicted top decile maximum flame lengths by 53%–224%. The custom fuel model performed somewhat poorer than GS3 or GR3, over-predicting top decile maximum FL by 26%. When fuel moistures and wind speeds observed in the field were used, ROS was also consistently over-predicted (Fig. 3). The custom fuel model over-predicted ROS by 20% at 0.68 m·s^{-1}, while GR7 over-predicted ROS by 518% at 3.50 m·s^{-1}. Of the standard fuel models, GS3 yielded the most accurate, but still under-predicted observed ROS by 28% at 0.41 m·s^{-1}. Based on Euclidean distance in parameter space, models

Table 4. Summary of fire behaviour observations. Observations were derived from video analysis of the prescribed fire in Kealakomo Waena in August 2011. The 90th percentile mean is a bootstrapped average.

	N	Mean	SD	SE	Range
Average flame length (m)	42	1.19	0.47	0.05	0.32–3.22
Maximum flame length (m)	42	2.17	0.8	0.15	0.97–4.41
90th percentile max flame length (m)	4	3.73	0.42	0.21	3.27–4.19
Rate of spread (m·s^{-1})	3	0.566	0.248	0.14	0.33–0.91

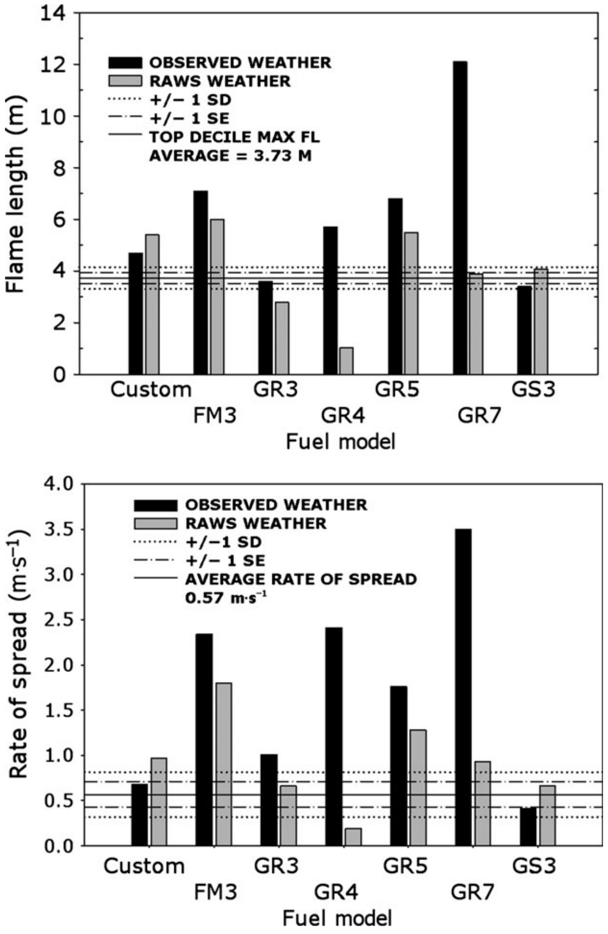

Fig. 3. Observed and predicted fire behaviour. Comparison of predicted and observed FL and ROS for each of the fuel models for each of the two fire weather and fuel moisture data. The predicted FL and ROS are shown by the vertical bars and the observed FL, calculated as the bootstrapped average of the top 10% of maximum FL measurements, and the observed ROS are shown by the horizontal solid line, for reference.

GR3 and GS3 produced fire behaviour most similar to the observed fire behaviour (Table 3).

The RAWS station indicated consistently higher 1-, 10- and 100-hr and lower live herbaceous and live woody fuel moistures than those observed *in situ*, and when using RAWS-derived fuel moistures and wind speed these differences in fuel moisture resulted in a lower overall range of predictions for both FL and ROS. Top decile FL was most accurately predicted by fuel model GR7 when using RAWS-generated fuel moisture and fire weather. Under these conditions, the custom fuel model performed less well than GR4, GR3 and GR7, and it over-predicted ROS by 71% and top decile FL by 45%. On the other end of the spectrum, Model 3 over-predicted ROS by 242% and top decile FL by 61%. Overall, ROS was best predicted by GS3 and GR3 (both 17% over-predictions).

Sensitivity to fuel moistures and wind speed

The wind and moisture scenarios were used to provide context over a range of conditions for both the custom and standard fuel models. These scenarios resulted in changes in predicted fire behaviour of larger magnitude than the SD of the observations (Fig. 4, Table 5). Reducing moistures and increasing wind speed separately and jointly increased ROS in both the custom and standard fuel models, with a much larger increase observed with the custom fuel model from 0.68 to 1.28 m·s^{-1} in the increased wind speed and decreased fuel moisture scenario. Reducing fuel moistures and increasing wind speed also increased FL up to 6.5 m in the custom model and to 4.6 m in the standard model. The fire behaviour under observed weather conditions was FL 3.7 ± 0.42 m and ROS 0.566 ± 0.246 m·s^{-1}. The largest predicted differences between the observed fire behaviour and the custom and standard fuel models were under the two most extreme scenarios of dryness (−25% fuel moisture and +25% wind speed) and moistness (+25% fuel moisture and −25% wind speed). The ±10% moisture and ±10% wind speed scenarios produced small changes in the custom fuel model. Furthermore, no threshold effects were observed near these combinations of fuel, moisture and wind speed parameters (e.g. Jolly 2007).

Discussion

Non-native grass invasion and subsequent fires have high potential to alter ecosystem structure (D'Antonio & Vitousek 1992; Tunison et al. 2001) and function (Mack & D'Antonio 1998; Mack et al. 2001). Significant efforts have been undertaken to quantify the biophysical factors associated with grass fire spread in Australia (Cheney et al. 1993, 1998), fire behaviour in grasslands and savannas of Brazil that include *M. minutiflora* (Kauffman et al. 1994; Mistry 1998) and the potential difference between vegetation types (Mistry & Berardi 2005). Kauffman et al. (1994) reported fire behaviour in communities containing

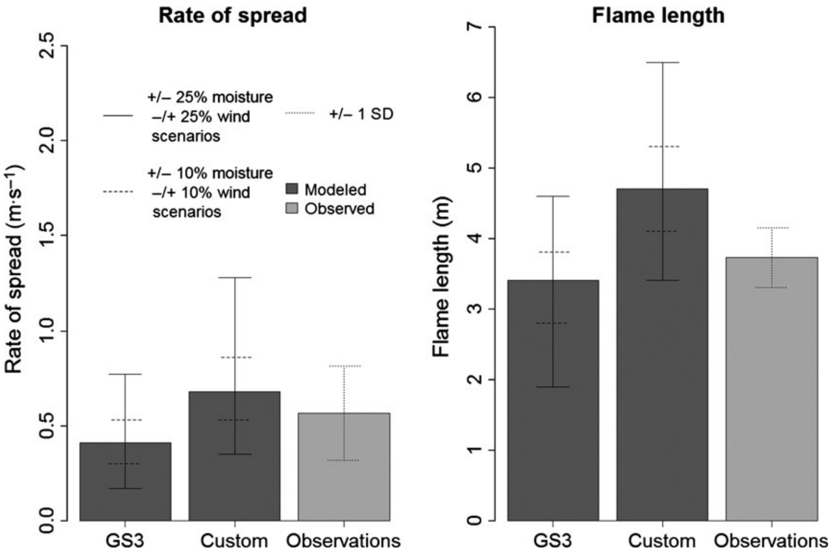

Fig. 4. Sensitivity analysis and observed fire behaviour. Comparison of predicted FL and ROS under observed conditions and the ±25% and ±10% moisture and wind conditions of the sensitivity analyses to the observed FL and ROS with SD. Note that only the two most extreme moisture and wind scenarios are shown for clarity of the figure.

Table 5. Summary of fuel moisture profiles used for the sensitivity analysis.

	Observed	−25%	−10%	+10%	+25%
1-hr (%)	8	6	7.25	8.8	10
10-hr (%)	9	6.75	8.1	9.9	11.25
100-hr (%)	10	7.5	9	11	12.5
Live herbaceous (%)	32	24*	28.8*	35.2	40
Live woody (%)	251	188.25	225.9	276.1	313.75**
Wind speed (km·h^{-1})	24	18	21.6	26.4	30

*The minimum fuel moisture accepted in BehavePlus® is 30, which is the value used to construct predictions for this moisture scenario. **Similarly, the maximum moisture accepted by BehavePlus® is 300, which is the value used to construct predictions for this moisture scenario.

M. minutiflora including flame lengths of 3–5 m and rates of spread in the range of 0.2–0.5 m·s^{-1}. However, Kauffman et al. (1994) did not compare observed fire behaviour to predicted fire behaviour.

In Hawai'i, Beavers' (2001) experimentally tested a fire behaviour fuel model for *M. maximus* and compared it to standard fuel models, and found that the standard fuel models were not accurate. This finding may relate to the general observation that tropical fuel complexes are extremely variable and necessitate their own suite of fuel models that lie outside of the range of standard fuel models for temperate ecosystems (Cochrane 2009b). The utility of standard fuel models in grass-invaded Hawaiian dry and mesic ecosystems is poorly understood (Beavers 2001), and to date they are rarely used by land managers and fire response personnel, especially at State and private levels.

Our fire behaviour modelling results show that standard fuel models used with easily accessed fire weather data (i.e. RAWS data) may perform adequately given the specific conditions of climate and fuel observed during our prescribed burns, but that observing fuel moistures and weather conditions in the field enhanced the accuracy of overall results. The small area available for the observation of fire was an important limitation to our study that reduced our ability to narrow the observation error. However, the weather and fuel conditions did not vary significantly from the time of the start of the fire to the time our observations were made. Using standard fuel model GS3 (Scott & Burgan 2005) coupled with *in situ* weather and fuel moisture data afforded better accuracy than the other standard models. The custom fuel model was similar to standard fuel model GS3, and produced similar fire behaviour predictions. Our model development conforms to the best practices described in Varner & Keyes (2009) as well as following the guidelines given by the original developers of BEHAVE (Burgan & Rothermel 1984).

There are many criticisms of custom fuel models (Varner & Keyes 2009; Cruz & Alexander 2010), known sensitivities to physical attributes of fuel (Jolly 2007; Reid & Robertson 2012), as well as attempts to re-parameterize fire behaviour prediction equations based on real grassland fires (Cheney et al. 1993, 1998). Despite these critiques, our custom fuel model produced similar predicted fire behaviour to the best-performing standard fuel models. Furthermore, our study represents a step towards a fully validated fuel model of non-native grass-invaded tropical dry shrublands, including demonstrating that such an effort might not necessarily improve upon already available standard fuel models. Judicious choice of standard fuel models, based on empirical evidence, may suffice for the purpose of fire prescription construction or general risk analysis. The ultimate choice between standard and custom fuel models will, however, be contingent upon further validation using prescribed fires or serendipitous natural events. As a result, in the absence of validation fires, the results of this study indicate that custom fuel models should be used where possible.

Both Cochrane (2009a) and Beavers (2001) stress that tropical fuel beds are vast and varied. In particular, spatial and temporal variation in tropical non-native grass fuels can be extreme (Ellsworth et al. 2013). It is possible that nearby grass–shrub mixtures in HVNP differ significantly from those in Kipuka Kealakomo Waena. In our case, it is suitable to use a single fuel model for describing the fuel complex on the date of the burn for this relatively small patch of vegetation as it is subject to uniform biophysical conditions, and for prescribed fires, average fuel condition as represented by a fuel model suffices for planning and prescription purposes. Model GS3 provided a relatively good prediction of fire behaviour using measured fuel moistures, but our results caution against using RAWS-reported weather. The fuel moisture model used in the NFDRS, which is implemented in the RAWS system, has also been shown to be inaccurate in a wide range of Hawaiian fuels (Weise et al. 2005). Fuel moistures in other Hawaiian fuels have been shown to be extremely variable in space and time, with little seasonal signal (Weise et al. 2005; Ellsworth et al. 2013). We suggest that, where possible, using field-measured fuel moistures will yield consistently more accurate predictions of fire behaviour. We understand that in many wildfire environments, managers are not able to collect field data – emphasizing the need for the development of a better and more accurate fuel moisture model in the tropics.

The moisture sensitivity analysis gives us confidence that model GS3 can be satisfactorily applied to this vegetation type because the intervals provided by that analysis fully captured the observed fire behaviour along with the observed standard deviations. Jolly (2007) examined the effect of changing fuel moistures on fire behaviour and found that model GS3 had moderate sensitivities to such changes with maximum sensitivities for FL near fuel moisture of 90% and for ROS near 30%. These sensitivities were lower than for other models with a higher live herbaceous load (Jolly 2007). In our analysis, combined with changes in wind speed, changes in fuel moisture of 25% produced overall changes in FL and ROS that are similar to Jolly (2007). Furthermore, we observed no evidence of rapid, threshold like changes in predicted FL and ROS while applying the moisture and wind speed adjustments.

Differences in fire behaviour predictions between the observed fuel moistures and the RAWS reported fuel moistures are due to an increase in 1- and 10-hr fuel moisture and a decrease in herbaceous and woody fuel moisture in the RAWS data as compared to the field data. Increased fuel moisture reported by RAWS in the 1- and 10-hr fuels suppressed ROS and increased FL in FM3, GR3, GR4, GR5 and GR7. On the other hand, decreased fuel moisture reported by RAWS in herbaceous and woody fuels increased ROS and decreased FL in the custom model and GS3.

Finally, increased ignition pressure from human use in HVNP is high and has increased exponentially since the late 1950s (Smith & Tunison 1992; Tunison et al. 2001). Coupled with well-known, non-native grass–fire cycle dynamics (D'Antonio & Vitousek 1992; D'Antonio et al. 2000; Tunison et al. 2001) and changes in fuel connectivity precipitated by grass invasions (Hughes et al. 1991; Diamond et al. 2009), the coastal lowlands of HVNP are likely well outside their historic range of natural variability for the frequency and severity of wildfires. Vegetation-driven changes in the fire regime itself (e.g. extent, frequency; Mack & D'Antonio 1998) have been shown to be enough to alter vegetation dynamics even in the absence of increased ignition pressure from humans (Keeley & Brennan 2012). Therefore, fire behaviour in invaded tropical coastal grasslands and shrublands of Hawai'i should remain a top management priority.

Conclusions

Our study highlights some of the difficulties of modelling fire behaviour in tropical fuel beds. In addition, fuel moisture response and seasonality differ significantly between tropical and temperate vegetation systems. It is important to note that although a standard model worked well in this case, our observations are only meaningful when assessed along with more observations of fire in grass-invaded coastal lowlands. A full validation of our custom fuel model was not possible in this case, which argues for more research on fire behaviour utilizing prescribed fires or fortuitous observations of wildfires in Hawai'i. However, since our custom fuel model was very similar to a standard fuel model, it may be the case that the careful application of standard fuel models plus the creation and validation of other custom models can potentially expand the scope of applicability of fire modelling in general in the tropics (e.g. Scott & Burgan 2005). In the absence of an effort such as ours, fire managers are left to uncritically apply RAWS data with standard fuel models, with largely unknown consequences. Careful study and quantification of these critical parameters can also advance the science of fire modelling in the islands of the tropical Pacific.

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