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Impact of grazing on fine fuels and potential wildfire behaviour in a non-native tropical grassland

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Abstract. Non-native grass invasion has increased fuel loads and fire frequency in areas throughout the tropics, resulting in a non-native grass–wildfire cycle with negative impacts on native biodiversity and ecological processes. *Megathyrsus maximus* (guinea grass) invades dry and mesic ecosystems throughout the tropics, increasing fuel loads and wildfire intensity. Eradication of *M. maximus* is difficult, making effective wildfire management critical to the protection of adjacent developed areas and remnant native ecosystems. The use of domestic livestock grazing in non-native grass ecosystems may be effective at decreasing fine fuel loads and potential wildfire behaviour. Our objectives were to: (1) quantify live and dead fine fuel loads and moistures in a *M. maximus*–dominated ecosystem before and after cattle grazing, and (2) use these data to model potential wildfire behaviour in grazed and ungrazed *M. maximus* grasslands with the BehavePlus fire modelling system. Fine fuel loads and moistures, climate variables, and predicted wildfire behaviour were quantified at the same site ($n = 1$) over two 5-month periods (March–July 2009, ungrazed; March–July 2010, grazed) in the Waiʻanae Kai Forest Reserve on the Island of Oʻahu, Hawaiʻi. Strong to conclusive evidence existed that cattle grazing in this system decreased dead and total fuel loads, but did not alter live fuel loads, or live and dead fuel moistures. Modelled wildfire behaviour under both low and average fuel moisture scenarios revealed that grazing decreased the potential rate of spread by 44–52% and flame length by 36–41%. These results demonstrate that cattle grazing may be an effective approach for reducing fuel loads and potential wildfire behaviour in non-native-dominated grasslands on tropical islands.

Additional keywords: BehavePlus fire model, guinea grass, invasive grass, *Megathyrsus maximus*, non-native grass–wildfire cycle, tropical dryland ecosystem.

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Introduction

Non-native grasses have been introduced throughout the world, and often lead to decreased native biodiversity (Flory and Clay 2010; Litt and Steidl 2010) and the establishment of an invasive grass–wildfire cycle (Brooks *et al.* 2004). Combined with increased anthropogenic ignition sources, non-native grass invasions now threaten native ecosystems globally by increasing the frequency and intensity of wildfires (Hughes *et al.* 1991; Mueller-Dombois 2001). This is particularly evident in lowland dry tropical ecosystems (Williams and Baruch 2000) where invasion and subsequent wildfire can result in monocultures of non-native grasses (D'Antonio and Vitousek 1992; D'Antonio *et al.* 2000; Ellsworth *et al.* 2014). In turn, non-native grasses often increase fuel loads, fuel continuity, and fuel packing ratios, which lead to more intense wildfires (Brooks *et al.* 2004). *Megathyrsus maximus* (Jacq.) R. Webster (guinea grass, previously *Panicum maximum* and *Urochloa maxima*) is a pastoral bunchgrass of African origin that was initially introduced for livestock grazing throughout South and Central America, the Caribbean, South-east Asia, and the South Pacific (Motta 1953; Sherley and Meyer 2000), and became naturalised in the Hawaiian Islands by 1871 (Motooka *et al.* 2003). Since its introduction, *M. maximus* has invaded dry and mesic ecosystems throughout the tropics, where it displaces native plant communities and alters wildfire regimes. Once established, eradication of *M. maximus* and restoration of native plant communities is exceedingly difficult (Ammondt and Litton 2012; Ammondt *et al.* 2013).

Most non-native grass eradication efforts rely on repeat herbicide applications and mechanical removal (Cabin *et al.* 2000; Ansari *et al.* 2008; Ammondt *et al.* 2013). A potentially cost-effective method for reducing fine fuel loads and wildfire potential in highly degraded non-native grasslands is through the use of domestic livestock grazing. While cattle grazing is often controversial (Marris 2011) and is largely considered incompatible with native species conservation in Hawaiʻi

(Scowcroft 1983; Cabin *et al.* 2000), the use of grazing to reduce fuel loads in non-native grasslands has been successful in at least some parts of the world (Leonard *et al.* 2010). Many non-native grass-dominated ecosystems in Hawai‘i and throughout the tropics currently have little to no remnant native species component (LaRosa *et al.* 2008). Reducing the occurrence and spread of wildfires in grass-invaded ecosystems is important for protecting surrounding developed areas and remnant native ecosystems. Effective use of livestock grazing to reduce wildfire potential in areas like Hawai‘i that evolved in the absence of large grazers should be used only where fuels are non-native and palatable forage, as is the case with *M. maximus*–dominated grasslands in Hawai‘i (Ansari *et al.* 2008).

The use of cattle grazing to reduce fuel loads and wildfire potential in non-native grasslands dominated by *M. maximus* has not been well studied, but successful examples exist from other ecosystems throughout the world. Livestock grazing has been used strategically to reduce fuel loads (e.g. in fire breaks) in native ecosystems (Davison 1996). Cattle grazing can effectively eliminate the potential for fast-spreading and intense fires via significant reductions in fuel loads and heights in tropical dry ecosystems with understoreys dominated by the non-native grass *Pennisetum clandestinum* Hochst. ex Chiov. (Kikuyu grass) (Blackmore and Vitousek 2000). Livestock grazing has also been shown to reduce fine fuel loads in other monotypic stands of invasive grasses (Diamond *et al.* 2009). As such, the use of cattle grazing to reduce fuel loads and wildfire intensity has the potential to be a valuable management tool in fire-prone, non-native-dominated grasslands in the tropics.

Potential fire behaviour is commonly modelled using fire models (i.e. BehavePlus 5.0: Andrews *et al.* 2005) that are parameterised with weather data and fuels collected *in situ* or with existing fuel models (Beavers 2001; Scott and Burgan 2005). Both custom and standard fuel models, however, are largely lacking throughout the tropics. BehavePlus allows users to input site-specific fuel and weather data to estimate potential behaviour (e.g. rate of spread, flame length) of existing fires, as well as to inform prescribed fire planning and fuel hazard assessments (Andrews *et al.* 2005). The BehavePlus fire-modelling system, like all fire models, is not without limitations (Kintisch 2013), but can provide valuable information for comparative studies such as this one.

The objectives of this study were to quantify live and dead fine fuel loads and moistures and model potential wildfire behaviour in a *M. maximus*–dominated tropical grassland before and after cattle grazing. We hypothesised that: (1) live and dead *M. maximus* fine fuel loads would be reduced by cattle grazing, and (2) reduced fuel loads with cattle grazing would decrease the rate of spread and intensity (i.e. flame length) of modelled wildfires. These hypotheses were tested by quantifying differences in fine fuels and modelled wildfire behaviour at the same site ($n = 1$) over two 5-month periods in 2009 (ungrazed) and 2010 (grazed) in the Wai‘anae Kai Forest Reserve on the island of O‘ahu, Hawai‘i. This research informs wildfire management in areas where non-native *M. maximus* dominates tropical ecosystems, where native species are largely absent, and where wildfire prevention and protection of adjacent ecosystems are high priorities.

Methods

Study area

This study was conducted from March 2009 to July 2010 in the Wai‘anae Kai Forest Reserve (21°28′48.32″N, 158°09′18.79″W) on the leeward slopes of the Wai‘anae Mountain Range on O‘ahu, Hawai‘i, USA. The study area is located at 258 m elevation with a mean annual temperature of 22.0°C (Giambelluca *et al.* 2014) and mean annual precipitation of 1258 mm (Giambelluca *et al.* 2013). Soils within the study area are classified as well drained, reddish silty clay loams of the Ewa series (Aridic Haplustolls) (NRCS). The fuel loads present consist primarily of 1- and 10-h fine fuels of a tropical grass (*M. maximus*) (~95% cover) that is known to be palatable to cattle (McCosker and Teitzel 1976), with sparse and small *Leucaena leucocephala* (Lam.) de Wit trees scattered throughout. Historically, the study area was a tropical lowland dry forest (Hatheway 1952), but it has been heavily degraded by non-native invasions, livestock grazing, and altered wildfire regimes to the extent that there is virtually no native plant component remaining.

The study area was designated as a State Forest Reserve in the early 1900s, which led to fencing and efforts to remove livestock over subsequent years. It is currently managed by the Hawai‘i Department of Land and Natural Resources with priority management goals including livestock exclusion and protection from wildfires. The Wai‘anae Kai Forest Reserve is adjacent to Hawai‘i Department of Agriculture land that is regularly leased for cattle grazing, and fences are poorly maintained. In August 2009, five months after fine fuel sampling began at this site (March–July 2009), an estimated 30 cattle (Holechek *et al.* 2010) entered the lower forest reserve (R. Peralta, Hawai‘i Department of Land and Natural Resources, pers. comm.). Grazing impacts were immediately evident where fuels sampling was already underway (Fig. 1). Actual grazing intensity is unknown, but cattle and their effects (trampling, grazed plants, bovine faeces) were readily evident in the area for the remainder of the study. We took advantage of this situation to quantify ungrazed (March–July 2009) and grazed (March–July 2010) fuel loads and moistures (see *Field data collection* for details). Data from the Wai‘anae Valley Remote Automated Weather Station, located ~30 yards (~27 m) from the study site at the same elevation, were used to parameterise the BehavePlus 5.0 fire model for each study period. The average wind speed observed across the entire 10-month sampling period (16.4 km h^{-1}) at the site was used for all fire model simulations (with and without grazing). The study site received 278 mm of precipitation in the two months before and during the ungrazed period, and 306 mm in the two months before and during the grazed period. Daily high air temperature was also very similar between study periods, averaging 28.0°C during the ungrazed period and 27.6°C during the grazed period.

Field data collection

Fine fuel load measurements included primarily *M. maximus*, along with other sparse fine fuels present within the study area. Woody fuels associated with *L. leucocephala* were minimal at the study site (Ellsworth *et al.* 2013) and were not quantified. Live and dead fine fuels were sampled weekly along a 50-m transect oriented parallel to the slope from March 2009 to July

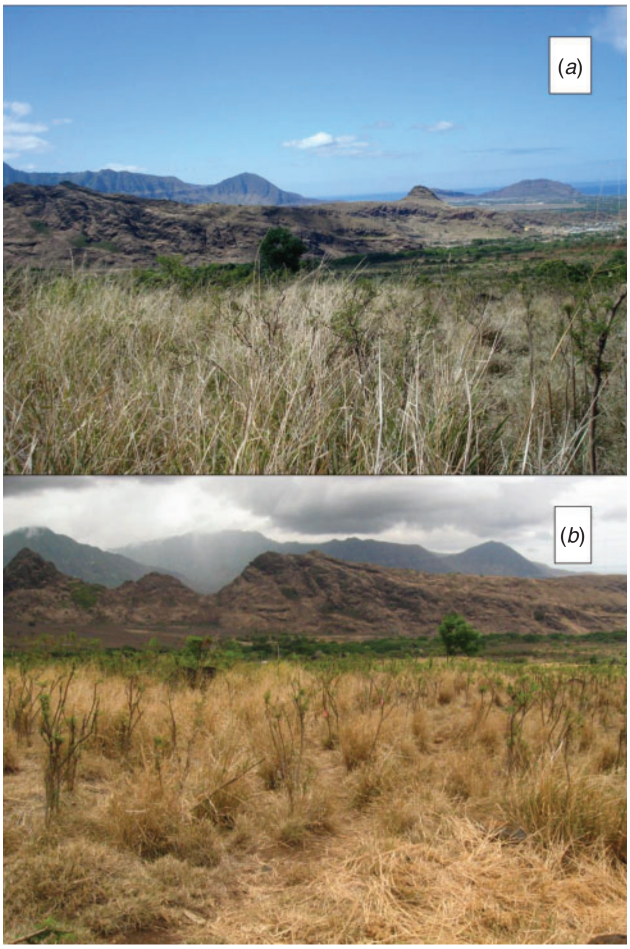

Fig. 1. Study location within a *M. maximus*–invaded ecosystem in the Wai'anae Kai Forest Reserve, O'ahu, Hawai'i, USA. (*a*) Ecosystem dominated by invasive *M. maximus* before cattle grazing, and (*b*) same *M. maximus*–dominated ecosystem following 5 months of cattle grazing, with noticeable consumption and trampling of fine fuels.

2009 ($n = 118$), and then monthly from March 2010 to July 2010 ($n = 28$; inspection of the 2009 data indicated that less intensive temporal sampling adequately captured temporal changes in fuels). We clipped live and dead standing grass and collected surface litter within 25 cm × 50 cm subplots down to the soil surface at six locations (0, 10, 20, 30, 40, and 50 m) along each transect. For each successive sampling period, the 50-m transect was offset by 1 m, parallel to the transect line from the previous sampling period.

All data necessary for custom fuel model parameterisation of BehavePlus 5.0 were collected, including live and dead 1-h fine fuel loads, live and dead fine fuel moisture, and fuel height (Table 1). Within 5 h of collection, samples were sorted into live and dead components, weighed, dried at 70°C for 48 h, and weighed again to determine fuel loads and moisture content. Fine fuel moisture content was calculated as the percentage of water present in each unit of dry fine fuel:

$$\left(\frac{S_W - S_D}{S_D}\right) \times 100 = \text{Fuel Moisture Content } (\%)$$

where S_W is the wet weight and S_D is the oven-dry weight of the sample (Pyne *et al.* 1996). Drying samples at 70°C and not 105°C, while commonly done, may lead to an underestimation of moisture content by as much as 3.5% (Matthews 2010). We averaged fine fuel data across subplots, and for 2009 across weeks, to obtain a value for each sampling month ($n = 5$ ungrazed values; $n = 5$ grazed values for each fuel parameter).

Wildfire modelling

BehavePlus 5.0.3 fire modelling software was used for all wildfire behaviour simulations (Andrews *et al.* 2005). Fuels, weather, and topography data collected during grazed and ungrazed periods were used as input parameters in a custom fuel model (Table 1). Live and dead fuel heat contents were measured by bomb calorimetry (Hazen Research, Inc., Golden, CO). Previously published values of dead fuel moisture of extinction and 1-h surface area to volume ratio for *M. maximus* were used (Beavers 2001). Because we wanted to quantify the effect of cattle grazing on fine fuel loads and moistures, all other fuel parameters except fuel bed depth were kept constant in simulations for ungrazed and grazed periods (i.e. 1-h surface area : volume (SA : V), live herbaceous SA : V, dead fuel moisture of extinction, live and dead fuel heat content, and slope steepness) (Table 1). We estimated the fuel bed depths for the ungrazed (0.59 m) and grazed (0.38 m) periods as 70% of the measured maximum grass heights across all subplots (Burgan and Rothermal 1984). Grazing could have also potentially altered canopy bulk density and fuel continuity, which were not quantified in this study. To capture the effect of fuel moisture, simulations were run with both an average (201% live, 32% dead fuel moisture) and an extreme (98% live, 14% dead fuel moisture) wildfire danger scenario for each month. Average and extreme fuel moistures used in simulations were based on actual average and minimum fuel moisture values measured at the study site (Table 1). Modelled fire behaviour output consisted of maximum rate of spread (m min^{-1}) and flame length (m) (an estimate of fire intensity).

Treatment comparisons

Because the study was opportunistic, and therefore not replicated, we used basic inference to examine differences in fuel loads, fuel moistures, and modelled fire behaviour between grazed and ungrazed periods. Means and 95% confidence intervals (CIs) were calculated for each variable across five-month study periods for ungrazed and grazed periods ($n = 5$) to place variables into one of four categories: (1) *convincing evidence* of a treatment difference existed if the 95% CIs for the two treatments did not overlap; (2) *strong evidence* of a treatment difference existed if the CIs overlapped, but the mean values for a given treatment fell outside of the CIs for the other treatment; (3) *inconclusive evidence* existed where the mean value for one treatment was within the CIs for the other treatment, but the second treatment mean was outside of the other treatment's CIs; and (4) *no evidence* of differences existed where the mean value of each treatment lay inside of the CIs for the other treatment (Ramsey and Schafer 2013).

Table 1. Input parameters for a custom fuel model in BehavePlus 5.0 for ungrazed and grazed *M. maximus*–dominated ecosystems in the Wai'anae Kai Forest Reserve, O'ahu, Hawai'i, USA

Italicised numbers indicate values that were left constant in grazed and ungrazed model simulations

		Ungrazed (March–July 2009)	Grazed (March–July 2010)
Fuel moisture (mean, minimum)			
Live fuel (%)		*201, 98*	*201, 98*
Dead fuel (%)		*32, 14*	*32, 14*
Fuel characteristics	Month		
1- and 10-h dead fine fuel load (Mg ha^{-1})	March	13.9	6.4
	April	12.3	10.1
	May	17.1	13.8
	June	19.2	10.7
	July	28.1	10.6
Live herbaceous fine fuel load (Mg ha^{-1})	March	3.1	1.3
	April	3.5	4.2
	May	4.9	4.7
	June	3.6	7.4
	July	5.5	2.7
Fuel bed depth (m)		0.585	0.379
Dead fuel moisture of extinction (%)		*40*	*40*
Dead fuel heat content (kJ kg^{-1})		*16282.0*	*16282.0*
Live fuel heat content (kJ kg^{-1})		*16747.2*	*16747.2*
1-h surface area : volume		*1200*	*1200*
Weather/terrain			
Midflame wind speed (mean) (km h^{-1})		*16.4*	*16.4*
Slope steepness (%)		*5*	*5*

Results

Fuel loads

There was no evidence that grazing altered live fine fuel loads, which averaged 4.12 Mg ha^{-1} without grazing (95% CI [3.21, 5.03]) and 4.07 Mg ha^{-1} with grazing (95% CI [2.06, 6.08]) (Fig. 2). There was convincing evidence that dead fine fuel loads were reduced by 43.1% with grazing, averaging 18.10 Mg ha^{-1} without grazing (95% CI [12.66, 23.54]) and 10.30 Mg ha^{-1} with grazing (95% CI [7.99, 12.61]) (Fig. 2). There was strong evidence that grazing reduced total fine fuel loads (dead + live fine fuels), which averaged 22.2 Mg ha^{-1} (95% CI [16.01, 28.43]) without grazing and 14.4 Mg ha^{-1} (95% CI [10.52, 18.22]) with grazing (Fig. 2).

Fuel moistures

There was inconclusive evidence that cattle grazing contributed to a 38.1% increase in live fine fuel moisture, which averaged 168.6% (95% CI [120.0, 217.0]) without grazing and 232.8% (95% CI [125.0, 341.0]) with grazing (Fig. 3). There was no evidence that dead fuel moisture (standing dead and litter) was altered by grazing, averaging 34.3% (95% CI [14.0, 55.0]) without grazing and 29.7% (95% CI [22.0, 37.0]) with grazing (Fig. 3).

Potential fire behaviour

There was convincing evidence that potential rate of fire spread was 44–52% lower with grazing under average and minimum fuel moisture scenarios (Fig. 4). Rate of spread averaged

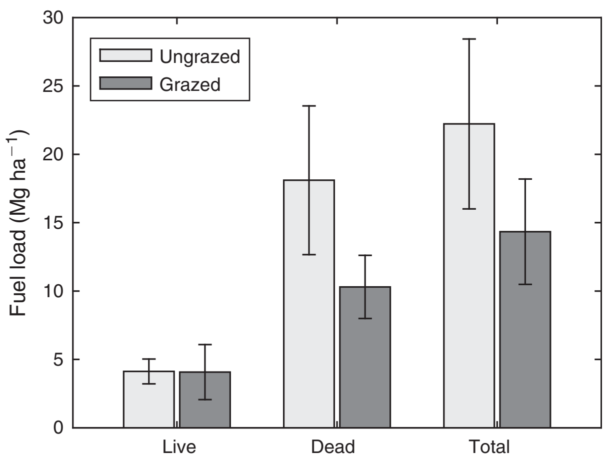

Fig. 2. Live, dead and total fine fuel loads in a *M. maximus*–dominated ecosystem in the Wai'anae Kai Forest Reserve, O'ahu, Hawai'i, USA, during ungrazed (light grey bars; March–July 2009) and grazed (dark grey bars; March–July 2010) periods. Dead fuel refers to a combination of standing dead and litter fuels. Bars are mean fuel loads and error bars are ±95% CIs.

2.28 m min^{-1} (95% CI [1.96, 2.60]) in ungrazed and 1.1 m min^{-1} (95% CI [0.8, 1.4]) in grazed conditions under average fuel moistures, and 5.66 m min^{-1} (95% CI [4.98, 6.34]) in ungrazed and 3.16 m min^{-1} (95% CI [2.51, 3.81]) with grazing under extreme fuel moistures. There was also strong evidence that flame lengths were reduced by grazing (Fig. 4),

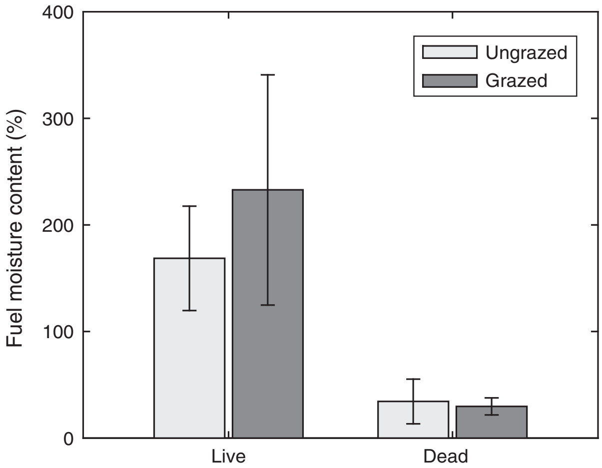

Fig. 3. Live and dead fuel moistures in a *M. maximus*–dominated ecosystem in the Wai'anae Kai Forest Reserve, O'ahu, Hawai'i, USA, during ungrazed (light grey bars; March–July 2009) and grazed (dark grey bars; March–July 2010) periods. Fuel moisture is expressed as a percentage of the oven-dry weight of the fuel. Bars are mean fuel moistures and error bars are ±95% CIs.

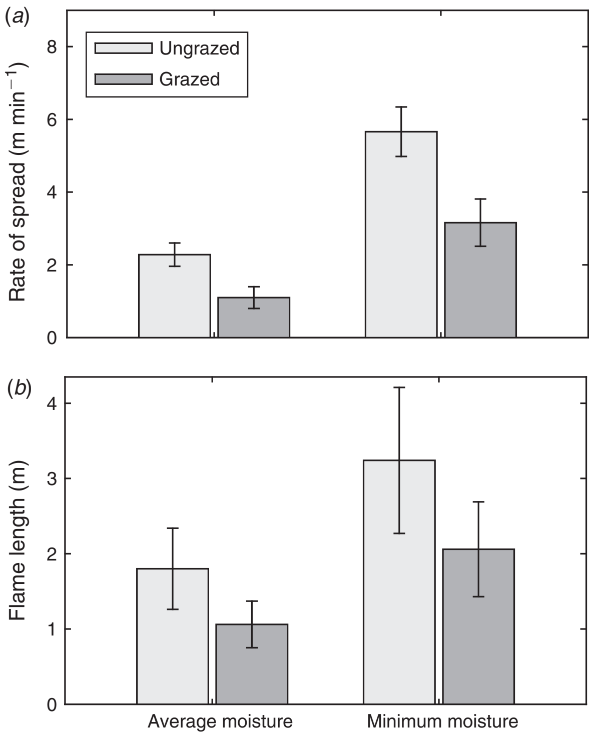

Fig. 4. BehavePlus-modelled fire behaviour using custom fuels models from *in situ* data. (*a*) Rate of spread and (*b*) flame length for ungrazed and grazed periods from the Wai'anae Kai Forest Reserve, O'ahu, Hawai'i, USA, using monthly fuel loads and average and minimum fuel moistures across study periods (i.e. ungrazed (light grey bars; March–July 2009) versus grazed (dark grey bars; March–July 2010)). Bars are mean values and error bars are ±95% CIs.

averaging 1.8 m (95% CI [1.26, 2.34]) without cattle grazing and 1.06 m (95% CI [0.75, 1.37]) with cattle grazing under average fuel moisture conditions, and 3.24 m (95% CI [2.27, 4.21]) without cattle grazing and 2.06 m (95% CI [1.43, 2.69]) with cattle grazing under extreme fuel moisture conditions.

Discussion

Overall, these results provide strong evidence that cattle grazing can reduce potential wildfire behaviour in non-native *M. maximus*–dominated dryland ecosystems in the tropics, as originally hypothesised. In particular, cattle grazing reduced dead fine fuel loads, which is the more flammable portion of the total fuel load that typically carries grassland fires (D'Antonio and Vitousek 1992). In this study, grazing impacted fuel loads by removing grass biomass via consumption, decreasing fuel heights, and ultimately reducing dead fine fuels, as seen in prior studies (Savadogo *et al.* 2007). To successfully reduce fuel loads with cattle grazing, the bulk of targeted biomass should be palatable fine fuels (i.e. 1- and 10-h fuels: Nader *et al.* 2007). Similar to this study, Leonard *et al.* (2010) found that cattle and other grazing animals reduced fuel loads and fire potential in native Tasmanian tussock and lawn grass ecosystems where the bulk of biomass was highly palatable. We were unable to control grazing pressure in this study, so it is not known what level of grazing pressure is needed to effectively reduce fine fuels and fire behaviour. However, our results are consistent with prior work demonstrating that targeted, intense cattle grazing is effective at reducing fine fuel loads in an ecosystem dominated by *M. maximus* and *L. leucocephala* in Hawai'i where grass cover was ≥60% (Ansari *et al.* 2008). In this prior study, cattle grazing reduced fine fuel loads and also resulted in a spatial discontinuity in fuels. Fuels were noticeably patchy following cattle grazing, resulting in 'fuel breaks' between thick *M. maximus* tufts, which would likely limit or slow fire beyond that estimated here.

Heavy fuel loads increase wildfire intensity in non-native grasslands (Lipponcott 2000; Brooks *et al.* 2004), and reducing fine fuel loads through grazing has been shown to be useful in some ecosystems. However, Castillo *et al.* (2007) found that a short period of cattle grazing had no lasting effect on fuel loading associated with the invasive *Cenchrus setaceus* (Forssk.) Morrone. (fountain grass) in an invaded Hawaiian dry ecosystem. *C. setaceus*, unlike *M. maximus*, is a poor forage species that is grazed by cattle only when it first flushes and no other forage is available (Bruegmann 1996). Longer-term measurements following cattle removal are needed to determine whether the grazing effect documented here in *M. maximus* grasslands would be similarly transitory, but it is quite likely that removal of cattle grazing would result in rapid increases in live and dead fine fuels. Further work examining necessary timing and levels of grazing pressure for reducing fuel loads are needed to better inform wildfire management in these and similar ecosystems.

In this study, grazing had no impact on dead fuel moisture, which is an important driver of wildfire occurrence and intensity. Our average dead fuel moisture values (30% ungrazed and 34% grazed) are higher than those previously reported for *M. maximus* in Hawai'i (Ellsworth *et al.* 2013). Sampling for this study encompassed both wet spring months and dry summer months, resulting in a wide range of measured fuel moistures. Regardless, the differences between grazed and ungrazed periods that we observed in fine fuel loads and potential wildfire behaviour are consistent with prior work demonstrating that grazing in non-native grass ecosystems can reduce fire intensity in tropical grasslands (Blackmore and Vitousek 2000).

While grazing appears to be effective at reducing fine fuel loads in grass-invaded dry tropical ecosystems, it is incompatible with conservation efforts for native species (Scowcroft and Giffin 1983). Non-native ungulates have been shown to have large, detrimental impacts on native plant communities in Hawai‘i (Daehler 2005; Cole *et al.* 2012; Cole and Litton 2014). Grazing to reduce fine fuel loads is also unlikely to be compatible with riparian ecosystem management, even where non-native species dominate (Kauffman and Krueger 1984). However, cattle grazing is a promising wildfire management technique in Hawai‘i and throughout the tropics where non-native grasslands dominate upland areas.

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