EFFECTS OF CATTLE GRAZING, GLYPHOSATE, AND PRESCRIBED BURNING ON FOUNTAINGRASS FUEL LOADING IN HAWAI'I

J. Michael Castillo
West Hawai'i Wildfire Management Organization, P.O. Box 6213, Kamuela, HI 96743-6213, USA

Gayland Enriques
U.S. Army, Installation Fire and Safety Office, 851 Wright Avenue, Wheeler AAF, HI 96857-5000, USA

Miles Nakahara
Hawai'i Department of Lands and Natural Resources, Division of Forestry and Wildlife, Kamuela State Tree Nursery, 66-1220A Lalamilo Road, Kamuela, HI 96743, USA

David Weise[1]
USDA Forest Service, Pacific Southwest Research Station, Forest Fire Lab, 4955 Canyon Crest Drive, Riverside, CA 92507, USA

Lawrence Ford
University of California–Santa Cruz, Environmental Studies Department, 5984 Plateau Drive, Felton, CA 95018-9253, USA

Rodrigo Moraga
Anchor Point Group, 3775 Iris Avenue, Suite 2A, Boulder, CO 80301, USA

Robert Vihnanek
USDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Lab, 400 N. 34th Street, Suite 201, Seattle, WA 98103, USA

ABSTRACT

Crimson fountaingrass (*Pennisetum setaceum*) is a nonnative invasive grass that has occupied a significant portion of the western side of the island of Hawai'i. As a result, several fires in excess of 4,049 ha have occurred in the area over the past 20 y. We are studying the effectiveness of cattle grazing, aerial application of glyphosate herbicide, and prescribed burning to reduce the fuel loading of fountaingrass in this dry, tropical setting. Grazing and prescribed burning were applied as whole-plot treatments to plots ranging in area from 2.4 to 6.5 ha; glyphosate herbicide was aerially applied as a split-plot treatment. Plots were burned in January and February 2004, aerially sprayed in March and May 2004, and grazed by cattle in March and April 2004. Fuels were sampled prior to treatment and at periodic intervals over the first year following treatment. Fuel and fire behavior variables were measured during the prescribed burns. Pre-treatment fuel loading ranged from 9 to 11 Mg/ha and fuel height averaged 0.5 m. Observed dead fuel moistures were 12–16% and live grass fuel moisture was >270% during the prescribed burns. Fire spread rates up to 16.8 m/min and flame heights up to 3.7 m were observed. Prescribed burning and glyphosate reduced fuel loads by 46% and 14%, respectively. Fuel height was reduced by 8–48%. Grazing did not have a significant effect in this study. Fuel height did recover and fuel loads did not recover to pre-treatment levels within 13 mo of the prescribed burns.

keywords: crimson fountaingrass, fire, flame length, fuels reduction, glyphosate, grazing, Hawai'i, leeward, *Pennisetum setaceum,* rate of spread.

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INTRODUCTION

In the tropics, grass invasions have been observed to cause increased fire frequency (McDonald et al. 1988, D'Antonio and Vitousek 1992, Smith and Tunison 1992). Grass invasions into dry vegetation communities of Hawai'i have resulted in recurrent wildfires that reduce woody plant cover and simplify plant community structure (Cuddihy and Stone 1990, Hughes et al. 1991, D'Antonio and Vitousek 1992, Castillo 1997). Resultant wildfires provide for increased solar radiation, higher near-ground wind speeds, and lower fine fuel moisture (Blackmore and Vitousek 2000). These conditions of higher fine fuel loads, lower fine fuel moisture, and higher near-ground wind speeds are conducive to fire ignition and spread (Freifelder et al. 1998).

Crimson fountaingrass (*Pennisetum setaceum*) was

[1] Corresponding author (dweise@fs.fed.us).

introduced into Hawai'i at the turn of the last century and now occupies >80,000 ha on the dry, leeward side of the island of Hawai'i. This grass invasion altered the surface fuel structure, which has increased the occurrence of large wildfires: five class G fires up to 4,000 ha have occurred in this area since the 1980s. Fountaingrass has also been introduced in the states of California, Arizona, New Mexico, Colorado, Tennessee, Florida, and Louisiana (USDA 2005). This introduction, along with several other invasive grass species, has resulted in fire spread into areas where fire occurrence was previously rare (Brooks and Pyke 2001).

Wildland fires ignited along road corridors present a threat to adjoining vegetation communities. Several herbicides are currently registered in Hawai'i for fountaingrass control; the active ingredients are diuron, hexazinone, imazapyr, and isopropylamine salt of glyphosate (National Pesticide Information Retrieval System 2006). Glyphosate (sold as Roundup®) has been used on the western side of Hawai'i to control fountaingrass (Motooka 2000, Cabin et al. 2002). In a study that evaluated the duration of cover reduction by various herbicides, a low rate of glyphosate applied to fountaingrass 3 mo after a wildfire reduced cover by 75% 2 y following treatment. The low rate of glyphosate was as effective as more intensive treatments such as herbicide and hand-pulling (Castillo 1997). Tunison (1992) reported that fountaingrass could be reduced in Hawai'i Volcanoes National Park with a great deal of labor by manually removing clumps.

There is some disagreement about the importance of fire in the evolution of Hawaiian biota (Vogl 1969, Loope 2000); however, it is well accepted that wildfire has deleterious effects on Hawaiian ecosystems. Prescribed fire was not recommended as a tool to eradicate fountaingrass (D'Antonio and Vitousek 1992); however, it is an effective tool to reduce fuel loading. The use and ecological impacts of cattle grazing and range management in Hawai'i are also well documented (Cuddihy and Stone 1990, Maly and Wilcox 2000). However, cattle reduce grass fuel loading if the grasses are palatable and could possibly be a commercially viable tool to reduce fuel loads in degraded areas dominated by introduced nonnative grasses. We established demonstration areas in western Hawai'i to illustrate the effectiveness and duration of these potential fuel treatments to reduce fountaingrass fuel loading. Because the primary fuel in the study area was fountaingrass and the intent of the project was to demonstrate the effectiveness of potential fuel treatments, large-scale treatments that might be applied operationally to grasslands were considered—prescribed fire, herbicides, and grazing. We present first-year results of this study to reduce the fuel loading of fountaingrass on the leeward side of Hawai'i.

STUDY AREA AND METHODS

Site Description

The study site was located in an extensive stand of fountaingrass located on the western side of the island of Hawai'i in the Pu'uanahulu Game Management Area (Figure 1). The vegetation in the game management area was very degraded relative to native plant populations. Lowland dry forest (Gagne and Cuddihy 1999) likely occupied the site prior to invasion by fountaingrass over the past 90 y. Remnant individual trees from the Hawaiian native dry forest are found within 4 km of the site. Average elevation of the site is 770 m, with a predominant west-facing aspect. The site is situated between two lava flows from Mauna Loa—the 1859 flow and the Ke'āmuku flow. The soils are histosols over lava with andisols (Gavenda et al. 1998). The average slope varies from 0 to 15% over most of the site.

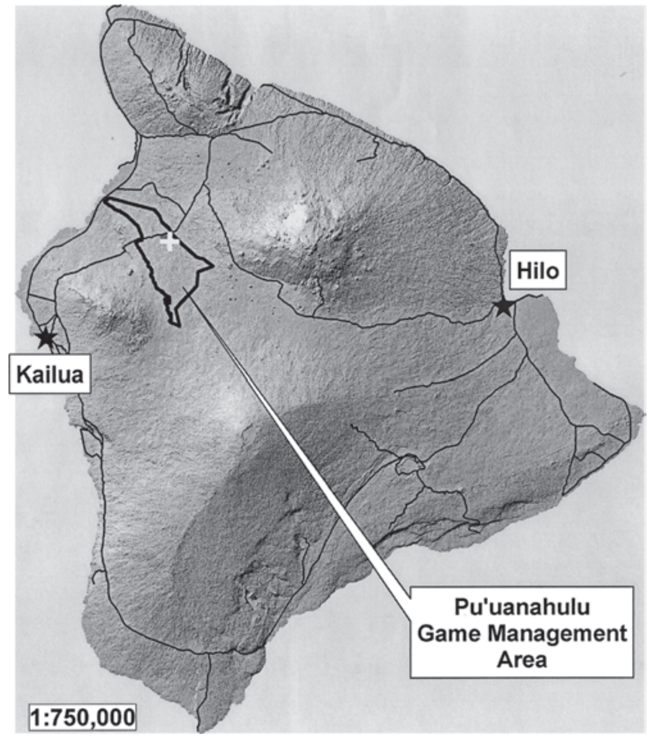


Fig. 1. A "+" identifies the approximate location of Pu'uanahulu Fuel Treatment Demonstration Area within the Puu An'ahulu Game Management Area, Hawai'i.

A remote automated weather station (RAWS) was established in April 2003 to record weather conditions at the site because the closest weather station was the Kailua-Kona Airport, which is located at sea level approximately 30 km southwest of the site. The monthly average temperatures and relative humidity for April 2003–August 2006 illustrate the relative stability of the climate (Table 1). Precipitation was recorded at the site for various times: 22.7 cm for 14 April 2003 to 28 January 2004, 44.1 cm for 19 April 2004 to 18 April 2005, and 33.0 cm from 19 April 2005 to 18 April 2006. This is similar to the average annual rainfall of 25–50 cm reported by Giambelluca and Schroeder (1998).

Table 1. Monthly summary statistics for Pu'uanahulu weather station, Hawai'i, from April 2003 to April 2006.

Month	Temperature (°C)			Relative humidity (%)		Solar intensity (W m^{-2})	
	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Jan	17.8	13.3	23.7	83.8	60.2	712	165
Feb	17.2	12.5	23.3	81.5	58.4	766	192
Mar	18.1	14.0	23.5	87.4	65.3	739	176
Apr	18.7	13.8	24.4	78.9	55.9	872	225
May	20.1	15.3	25.5	80.1	57.7	867	224
Jun	20.5	15.6	26.1	79.4	57.1	826	219
Jul	21.1	16.2	26.7	78.0	55.3	881	235
Aug	21.6	16.6	27.6	77.9	55.2	908	233
Sep	21.4	16.4	27.3	77.5	54.7	888	225
Oct	20.5	15.8	26.4	79.3	55.1	784	192
Nov	19.6	15.0	25.3	81.5	58.7	673	160
Dec	18.3	13.7	24.2	79.1	55.0	651	154

Study Design

In order to provide a fuel break along the Mamalahoa Highway to reduce the risk of fires spreading from the road upslope to native plant reserves located in the U.S. Army Pohakuloa Training Area (Shaw et al. 1997), the study plots were established on the upslope side of the highway. Combinations of prescribed burning–no burning and grazing–no grazing were applied as whole-plot treatments, and glyphosate herbicide was applied as a split-plot treatment in a factorial design with three replications of complete blocks (Figure 2). The treatments were numbered at the split-plot treatment level (1–8). Each block consisted of four whole plots and eight split plots. Locations of the whole plots were restricted to reduce the total area fenced and to minimize the number of prescribed burns conducted. In the idealized design (Figure 2), a total of six plots would have been burned (three blocks × two plots). However, four of the burns were applied to the whole plots in blocks 1 (burns A, B) and 3 (burns C, E), and one burn (D) was used to burn both whole plots in block 2. The total area of the experiment was approximately 35 ha. Table 2 lists the plots and the fuel treatments applied. The repeated-measures linear model describing the idealized experimental setup contained both fixed and random effects (Equation 1). Repeated-measures analysis of variance was used to test the significance of the effects in this model. The probability level associated with significant effects was set to 0.05.

$$y_{ijklm} = \mu + W_i + \beta_j + \gamma_k + \beta_j\gamma_k + \eta_l + \beta_j\eta_l + \gamma_k\eta_l + \beta_j\gamma_k\eta_l + \tau_m + \beta_j\tau_m + \gamma_k\tau_m + \beta_j\gamma_k\tau_m + \eta_l\tau_m + \beta_j\eta_l\tau_m + \gamma_k\eta_l\tau_m + \beta_j\gamma_k\eta_l\tau_m + e_{ijklm}, \quad (1)$$

where W = block, β = burning, γ = grazing, η = herbicide, τ = time effect, and e = error. The block effect, W, was treated as a random effect to account for the restrictions on treatment location. The significance of the burning (β) and grazing (γ) effects was tested using the sum of squares of the plots within each block, and the significance of the glyphosate (η) effect and its interactions was tested using the residual error sum of squares. Means for each treatment effect were estimated as linear combinations of the least-squares estimates. The significance of the difference between a treatment mean and its control (no treatment) was tested for all treatment combinations using t-tests. The F-statistics associated with the terms in Equation 1 test a different hypothesis—equality of all levels of a treatment combination (i.e., H_0: $\beta_0 = \beta_1 = 0$ or H_0: $\beta_0\gamma_0 = \beta_0\gamma_1 = \beta_1\gamma_0 = \beta_1\gamma_1 = 0$).

The five prescribed burns were conducted in January 2004, grazing was applied in late April and May 2004, and glyphosate herbicide was applied aerially to areas that would not receive grazing in March, and to grazed areas in May 2004. The burn prescription required a 6.1-m wind speed of 8.3–16.7 km/h from the north, which yielded a midflame wind speed of 5–10 km/h, relative humidity of 60–70%, air temperature of 13–20°C, and 1-h dead fuel moisture content of 15–18%. This prescription was derived using the BEHAVE program to define fuel and weather variables based on desired rate of spread or flame length (Andrews 1986). A black line was established on the downwind side, followed by flank ignition and strip headfires to complete the burning.

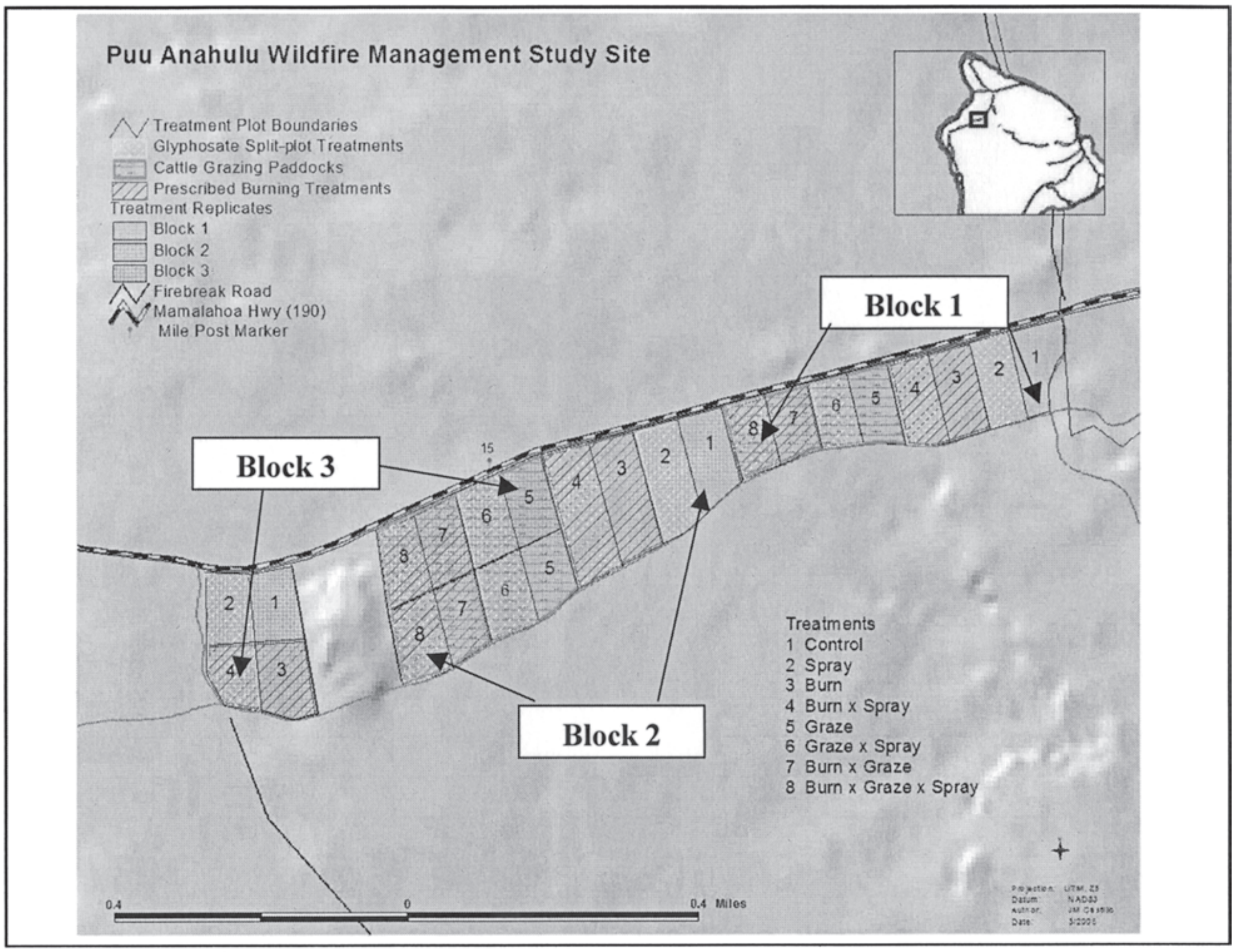
Cattle grazing was applied as a light-intensity pulse graze for a period of 26 d at a rate of 0.24 to 0.32 animal-unit mo. Animals were confined to unburned portions of each plot for the first 6 d and then allowed free choice between burned and unburned areas for the remaining 20 d. Glyphosate was applied at the rate of 2.8 kg active ingredient/ha from a Hughes 500D helicopter equipped with a 9.1-m boom sprayer.

Treatment Fuel Sampling

Average height, absolute cover of all herbaceous material, and fuel loading were measured on 10 randomly located 1-m^2 samples within a split plot (Ford 2005). Fuel loading samples were collected by clipping all material in the square meter and weighed in the field to determine wet weight. A subsample of the fuel load sample was weighed in the field to determine wet weight, was oven-dried at 70°C to a constant weight, and then was reweighed to determine dry weight. Oven safety concerns prevented drying samples at a higher temperature. Subsample moisture content was determined on an oven-dry basis and used to estimate the sample's dry mass. Each split plot was sampled four times: prior to burning (January 2004), after grazing and herbicide applications (February to May 2004), in August 2004, and in March 2005.

Fire Behavior Measurements

Weather, fuel moisture, rate of spread, and flame length data were collected for each of the six plots that were burned. Weather data were recorded by two automatic weather stations located within 0.5 km north and south of the plots and out of the influence of the smoke. Weather data were also collected manually throughout the burns using a sling psychrometer and handheld anemometer typically found in a belt weather kit. Immediately prior to ignition, fuel moisture samples were collected by clipping the live grass that con-



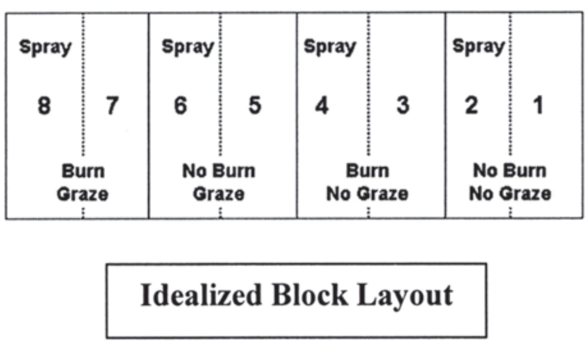


Fig. 2. Actual and idealized treatment designs to reduce crimson fountaingrass fuel loading for Pu‘uanahulu Wildfire Management Study, Hawai‘i, 2004–2005.

stituted most of the fuel bed and placing the samples in a moisture-tight Nalgene® bottle (Nalge Nunc International, Rochester, NY) for later processing. Fuel moisture content was determined by drying 5- to 10-g subsamples from each bottle in a Computrac® Max 1000 moisture analyzer (Arizona Instrument, Tempe, AZ). Rate of spread was estimated for various segments of uniform fuels by measuring time and distance. Flame length was recorded using a video camera. A target of known size was placed in the plot to estimate flame length from the imagery.

RESULTS

Mean (± SE) oven-dry fuel loadings of the grass and herbaceous fuels prior to treatment in January

Table 2. Treatments to reduce crimson fountaingrass fuel loading, Pu‘uanahulu Game Management Area, Hawai‘i, 2004–2005.

Treatment no.	Prescribed burn	Grazing	Glyphosate
1	No	No	No
2	No	No	Yes
3	Yes	No	No
4	Yes	No	Yes
5	No	Yes	No
6	No	Yes	Yes
7	Yes	Yes	No
8	Yes	Yes	Yes

2004 were 11.9 ± 1.0, 9.8 ± 1.3, and 9.5 ± 1.6 Mg/ha for the three blocks (n = 4) (Table 3). Initial fuel heights were 0.55 ± 0.02, 0.47 ± 0.04, and 0.57 ± 0.04 m. The initial fuel loadings and fuel heights did not differ significantly between blocks. Moisture content of the samples averaged 52 ± 2% across the three blocks. The fuel moisture samples were a composite of litter, standing live herbaceous material, and dead fountaingrass.

Prescribed Fire Behavior

From 1 September 2003 to 25 January 2004, 21 cm of rain were recorded by the RAWS, resulting in fountaingrass that was vigorous, in flower, and very green in color at the time of the burns. While fuel moistures measured to estimate fuel loading averaged 52%, the fuel moisture of the predominantly live grass was >270% (Table 4). Dead fuel moisture content fell in the 12–16% range during the prescribed burns.

The plots were burned over an 8-d period from 27 January to 4 February 2004. The first plot treated was difficult to burn. Conditions, although in prescription, were marginally sufficient for burning, and a large percentage of the plot had to be ignited (Table 4). Multiple strip headfires were lit on a very close spacing (5–10 m between strips). This plot was the first prescribed burn conducted by the Hawai‘i Division of Forestry and Wildlife on Hawai‘i, so due caution was taken to minimize escape. The observed spread rates for this plot ranged from 0.7 to 2.3 m/min, and approximately 40% of the fuel was consumed (Table 5). As Division of Forestry and Wildlife personnel's experience increased, more aggressive burning occurred, resulting in greater spread rates up to 16.8 m/min, flame heights of 2.7 to 3.7 m, and fuel consumption up to 90%.

Impact of Treatments on Fuel Loading and Fuel Height

Fuel loadings and heights were estimated following the application of the final treatment (March to May 2004) and 6 and 13 mo after the prescribed burns (August 2004, March 2005) (Table 3). The repeated-measures analysis of variance indicated that only the burn treatment and the burn × time interaction significantly affected fuel loading (Table 6; significant if $P < 0.05$). The time effect was also significant, indicating that the average loading on the site (average of all plots) differed over the four measurement times. The significant burn × time interaction indicated that the change in fuel loading over time differed between the

Table 3. Estimated fine fuel loading pre-treatment and for 1 y following fuel treatment application to reduce crimson fountaingrass in the Pu‘uanahulu Game Management Area, Hawai‘i, 2004–2005.

Treatment				Fuel loading (Mg/ha)[a]							
				Jan 2004		May 2004		Aug 2004		Mar 2005	
Burn	Grazing	Herbicide	Block	Mean	SE	Mean	SE	Mean	SE	Mean	SE
N	N	N	1	9.8	1.3	10.9	0.9	16.1	1.1	12.5	1.0
			2	6.2	2.5	10.1	2.2	12.8	1.9	6.3	1.6
			3	8.0	1.6	6.5	2.0	6.8	0.9	4.8	1.0
N	N	Y	1	12.3	1.3	11.3	2.0	12.0	2.3	7.1	1.1
			2	4.4	1.8	7.9	2.4	9.4	2.2	4.6	1.6
			3	8.4	1.3	7.6	1.5	8.9	2.3	5.9	1.5
Y	N	N	1	14.4	2.6	4.4	1.8	4.7	0.8	4.1	0.7
			2	8.1	3.1	0.5	0.1	2.8	1.2	2.0	0.7
			3	10.5	4.3	1.3	0.3	3.7	0.7	2.7	0.4
Y	N	Y	1	16.2	3.6	1.7	0.5	1.9	0.9	1.7	0.4
			2	13.8	2.6	0.8	0.4	1.8	0.5	1.2	0.2
			3	11.7	2.3	2.2	0.4	1.7	0.2	4.3	0.8
N	Y	N	1	7.4	2.4	9.9	3.1	11.2	2.6	5.1	1.4
			2	9.6	2.3	14.2	2.7	18.9	3.5	6.2	1.2
			3	8.1	2.1	17.0	4.4	10.8	3.2	4.0	1.2
N	Y	Y	1	12.0	2.6	9.6	2.2	12.3	2.7	4.7	1.2
			2	4.4	1.2	6.4	2.1	11.3	2.0	8.7	2.2
			3	3.8	1.2	3.0	1.2	10.6	2.8	5.7	1.6
Y	Y	N	1	10.3	1.8	2.1	1.1	2.4	1.0	3.3	0.8
			2	14.0	2.4	0.7	0.2	1.8	0.3	1.7	0.4
			3	15.5	2.9	1.5	0.3	4.0	0.8	3.5	0.6
Y	Y	Y	1	12.6	2.8	0.5	0.1	1.4	0.7	1.6	0.7
			2	15.2	2.4	0.8	0.2	1.0	0.2	1.9	1.0
			3	12.7	1.8	0.6	0.2	2.0	1.0	1.4	0.5

[a] Values are plot mean and within-plot standard error (n = 10). 1 Mg/ha = 1 metric ton/ha = 0.45 English ton/acre.

Table 4. Estimated fuel and weather conditions during prescribed burns in crimson fountaingrass near Pu'uanahulu, Hawai'i, in 2004.

Block	Treatment no.[a]	Date	Time	Status[b]	Moisture content (%)	Temperature (°C)		Relative humidity (%)
						Air	Fuel	
1	3, 4	28 Jan	1050	D	14.4	21.3	26.5	66
1	7, 8	3 Feb	1000	D	15.3	19.5	23.8	66
1	7, 8	3 Feb	1000	L	277.7	19.5	23.8	66
1	7, 8	3 Feb	1240	D	13.7	19.9	20.4	71
2	3, 4	3 Feb	1445	L	275.3	19.8	18.9	74
2	3, 4	3 Feb	1520	D	13.9	19.4	19.1	73
2	3, 4	3 Feb	1645	D	12.7	20.0	19.7	72
2, 3	7, 8	4 Feb	1000	D	16.0	19.7	24.7	71
2, 3	7, 8	4 Feb	1000	L	288.5	19.7	24.7	71
3	3, 4	27 Jan	1130	D	13.5	23.1	30.7	55
3	3, 4	27 Jan	1230	L	288.3	21.2	25.8	74

[a] Treatment no.: 3, burned; 4, burned and glyphosate applied; 7, burned and grazed; 8, burned, grazed, and glyphosate applied.
[b] Status: D, dead; L, live.

burned and unburned plots (Figure 3a). The *P*-value of the herbicide × time interaction (0.062) was slightly greater than our level of significance, and *P*-values for some of the tests of the higher order interaction terms fell in the range $0.10 > P > 0.05$. The herbicide × time interaction suggests that the temporal change in fuel loading on the split plots treated with glyphosate was different from the temporal change on the split plots not treated with glyphosate.

The mean fuel loadings estimated by least squares for each treatment and various combinations of treatments ranged from 4.3 to 9.7 Mg/ha (Table 7). Mean fuel loadings for all treatment combinations with prescribed fire were significantly less than the corresponding unburned control mean. The mean loadings for the grazing and glyphosate treatments were not statistically different from the untreated control. Averaged over the entire experiment, prescribed burning reduced fountaingrass fuel loading by 46%, grazing did not reduce fuel loading, and glyphosate reduced fuel loading by 14% (Table 7).

Mean fuel heights for all treatments except grazing alone were significantly less than the corresponding untreated mean heights (Table 7). Mean fuel height reduction ranged from a low of 8% (Table 7: G [grazing]) to a high of 48% (Table 7: BGH [burning, grazing, glyphosate]). When averaged over the entire experiment, prescribed fire reduced fuel height by 23% and glyphosate reduced fuel height by 17%. Species composition data were collected but not presented here. These data have yet to be analyzed; however, visual inspection of the plots suggested that the glyphosate treatment had a significant effect on species composition. Glyphosate killed most if not all of the fountaingrass. However, the dead standing grass was still present and contributed to fuel loading 1 y following application.

The main effect of the grazing treatment did not significantly affect fuel height by itself. However, the grazing effect appeared in several significant temporal interaction terms (Table 6). The significant interaction terms with time indicate that the temporal response of fuel height to the fuel treatments differed (Figure 3b). The height of the untreated fountaingrass was relatively constant over time; the grazed plots also changed little over time. In contrast, the fuel height of the burned plots decreased significantly initially following the burns, then recovered to the pre-treatment height within 13 mo post-treatment.

Table 5. Observed fire behavior and visually estimated fuel consumption in prescribed burns in crimson fountaingrass stands near Pu'uanahulu, Hawai'i, in 2004.

Date	Block	Treatment no.[a]	Spread rate range (m/min)	Flame height range (m)	Fuel consumption (%)
27 Jan 2004	3	3, 4	0.7–2.3	0.3–1.5	40
28 Jan 2004	1	3, 4	0.7–12.1	0.6–2.7	90
3 Feb 2004	1	7, 8	0.7–12.1	0.9–3.7	80
3 Feb 2004	2	3, 4	0.7–16.8	0.9–3.7	65
4 Feb 2004	2, 3	7, 8	1.0–13.4	1.5–3.0	80

[a] Treatment number: 3, burned; 4, burned and glyphosate applied; 7, burned and grazed; 8, burned, grazed, and glyphosate applied.

Table 6. Summary of independent *F*-tests of the effect of burning, grazing, and herbicide treatments and repeated measurements on crimson fountaingrass fuel loading and fuel height near Pu'uanahulu, Hawai'i, in 2004.

Effect[a]	Fuel loading			Fuel height		
	df[b]	*F*[c]	Pr > *F*	df	*F*	Pr > *F*
Block	2/6	1.31	0.337	2/6	2.13	0.156
Burn	1/6	26.20	0.002	1/6	20.59**	0.001
Grazing	1/6	0.00	0.972	1/6	1.84	0.196
B*G	1/6	0.07	0.804	1/6	1.49	0.242
Herbicide	1/8	3.11	0.116	1/6	10.19**	0.007
B*H	1/8	1.25	0.297	1/6	0.50	0.491
G*H	1/8	0.99	0.349	1/6	2.62	0.128
B*G*H	1/8	0.13	0.732	1/6	3.13	0.099
Time	3/48	48.15**	<0.001	3/48	37.45**	<0.001
B*T	3/48	73.93**	<0.001	3/48	76.23**	<0.001
G*T	3/48	0.51	0.674	3/48	3.71	0.018
B*G*T	3/48	1.52	0.222	3/48	4.33**	0.009
H*T	3/48	2.61	0.062	3/48	25.63	<0.001
B*H*T	3/48	1.16	0.333	3/48	2.99**	0.040
G*H*T	3/48	2.25	0.094	3/48	5.00**	0.004
B*G*H*T	3/48	2.24	0.095	3/48	2.36	0.083

[a] Abbreviations: B, prescribed burning; G, cattle grazing; H, glyphosate herbicide; T, time.
[b] Numerator degrees of freedom/denominator degrees of freedom.
[c] *F*-statistic calculated using Type 3 (partial) sums of squares.
** *F* significant if $\alpha \leq 0.05$.

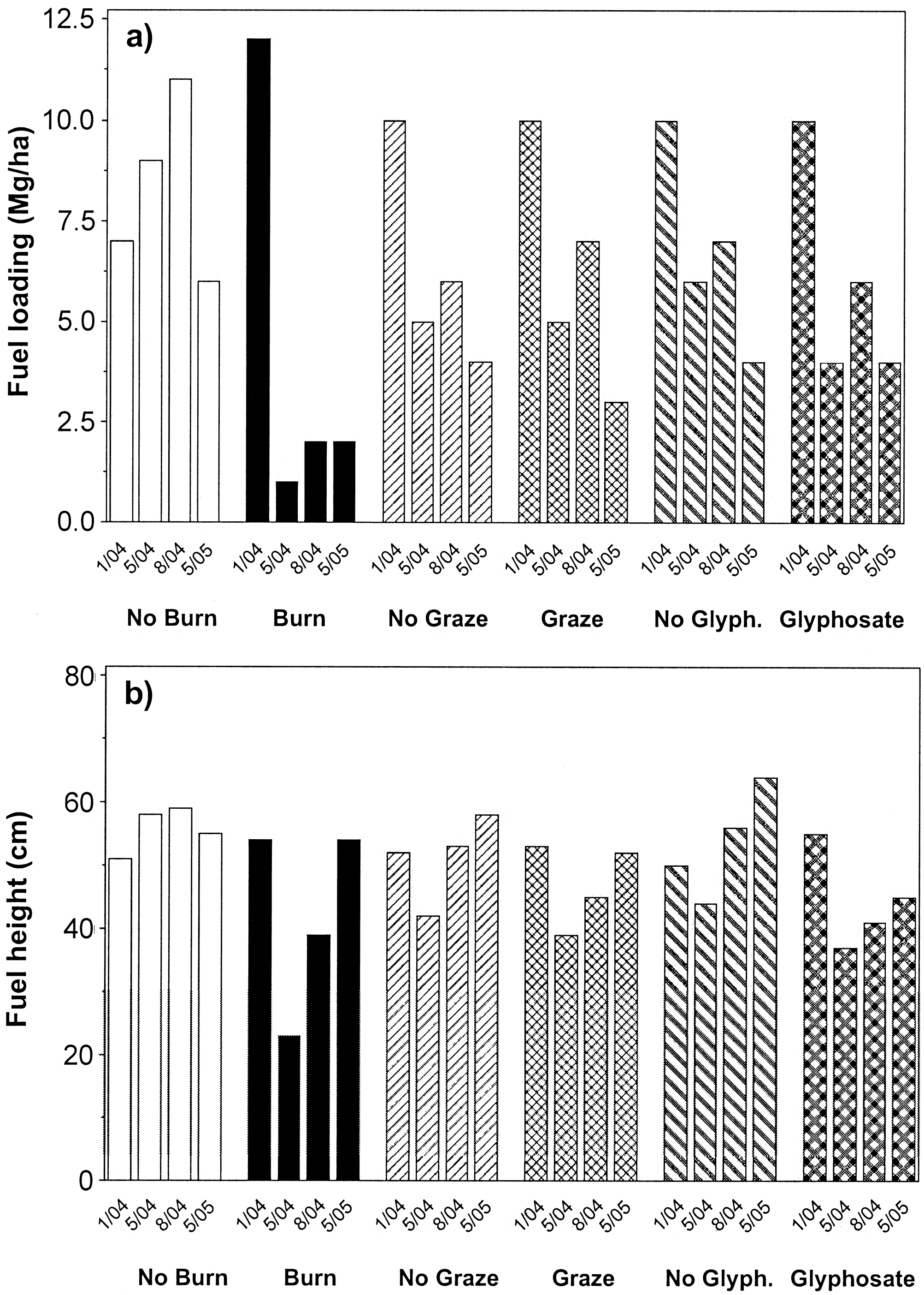


Fig. 3. Impact of prescribed burning, light cattle grazing, and glyphosate herbicide on (a) fine fuel loading and (b) fuel height to control crimson fountaingrass near Pu'uanahulu, Hawai'i, 2004–2005. The values plotted are effect means estimated as linear combinations of the least-squares estimates.

DISCUSSION AND MANAGEMENT IMPLICATIONS

The uniqueness of native Hawaiian terrestrial biodiversity is unparalleled compared to that of other oceanic island archipelagos and is recognized as one of the world's biodiversity "hotspots." Hawai'i's highly varied climate, extreme geographic isolation, geological history, and broad range of habitats have interacted to form a highly diversified and unique biota. Hawai'i's high rate of floristic endemism has provided for unique plant communities dominated by native species (Gagne and Cuddihy 1999). Tropical dry ecosystems are considered to be the most endangered ecosystem on the earth (Janzen 1988).

The glyphosate treatment resulted in good coverage and uniform kill. As a result, the glyphosate-treated split plots had well-defined edges (Figure 4). Application of the grazing treatment was not as successful as the prescribed burning or herbicide treatments.

Table 7. Summary of pairwise comparisons of estimated effect means between control and each treatment combination for fuel loading and fuel height. Significant if $\alpha \leq 0.05$. For brevity, only significant 3-factor interaction terms listed.

Treatment code[a]	Loading (Mg/ha)					Height (m)				
	Mean	Control	Reduction[b]	t[c]	Pr > |t|	Mean	Control	Reduction	t	Pr > |t|
B	4.8	8.9	46	−5.12	0.002	0.43	0.56	23	−4.54	0.000
G	6.8	6.8	0	−0.04 ns	0.972	0.48	0.52	8	−1.36 ns	0.196
Bg	4.9	8.8	44	−3.44	0.014	0.43	0.60	28	−4.07	0.001
BG	4.7	8.8	46	−3.64	0.011	0.43	0.60	28	−4.17	0.001
H	6.3	7.3	14	−1.76 ns	0.116	0.45	0.54	17	−3.19	0.007
bH	8.0	9.7	18	−2.04 ns	0.076	0.51	0.62	18	−2.76	0.015
Bh	5.0	9.7	48	−4.77	0.001	0.47	0.62	24	−3.71	0.002
BH	4.6	9.7	53	−5.16	0.000	0.40	0.62	35	−5.47	0.000
GH	6.0	7.1	15	−1.08 ns	0.300	0.41	0.54	24	−3.22	0.006
bGH	7.7	9.2	16	−1.09 ns	0.297	0.47	0.66	29	−3.24	0.006
Bgh	4.9	9.2	47	−3.08	0.010	0.42	0.66	36	−4.12	0.001
BgH	4.9	9.2	47	−3.08	0.010	0.45	0.66	32	−3.67	0.003
BGh	5.1	9.2	45	−2.97	0.012	0.51	0.66	23	−2.49	0.025
BGH	4.3	9.2	53	−3.52	0.004	0.34	0.66	48	−5.43	0.000

[a] Uppercase letter denotes presence of treatment; lowercase letter denotes absence. Abbreviations: B, prescribed burning; G, cattle grazing; H, glyphosate herbicide.
[b] Reduction = 100[1 − (mean/control)].
[c] Student's t. ns, t is not significant if $\alpha > 0.05$.

Fig. 4. Precision of aerial spraying of glyphosate herbicide (left) to control crimson fountaingrass near Pu‘uanahulu, Hawai‘i, in 2004.

Grazing intensity was light due to changing livestock ownership and ranch lease agreements at the time of treatment and difficulty in obtaining the number of animals needed to achieve the desired stocking rate. Grazing pressure was not uniform because of the high preference that the cattle displayed for the new growth in the burned plots. In addition, gates between the fenced grazing plots remained open, so grazing use and forage selection were not consistent between the different plots. It was difficult to determine the grazing pressure; therefore, the grazing results are of limited value.

Preliminary results indicated that prescribed burning is an effective tool to reduce fuel loading in fountaingrass. However, there is an element of risk associated with the use of prescribed burning. In this area of Hawai‘i, there are few roads to interrupt fuel continuity. An escaped prescribed burn could easily spread 15 km to the east in <24 h under the influence of westerly onshore breezes that circulate under the predominant northeastern trade winds. At least five wildfires have burned in such a fashion over the past 20 y, threatening native plant reserves such as the Kīpukakalawamauna Endangered Plants Area located in the Pohakuloa Training Area (Shaw et al. 1997). Because of risk of escape, the natural resources at risk, and the limited experience with prescribed fire use in this area, the per-unit cost of fire use is likely greater than in areas with less risk and more experience. The duration of the fuel load reduction caused by the prescribed burn treatment is currently unknown and cannot reliably be estimated from these data. The frequency at which prescribed fire should be applied to maintain reduced fuel loadings also influences per-unit costs.

Grazing has been shown to be an effective tool to reduce fuel loads in grass and herbaceous plants (Hatton 1920, Blackmore and Vitousek 2000). Palatability and nutritive content of the plants is an important consideration. We observed the cattle preferring the new green growth following the prescribed burns instead of the dried fountaingrass. In our study, cattle grazing was low intensity, weakly managed, and of brief duration. Cattle utilized the burned areas more than the unburned areas. Assisted by favorable growing conditions, lightly grazed areas recovered quickly. A grazing system utilizing a rotational grazing scheme has been used at Pu‘uwa‘awa‘a, an area just west of Pu‘uanahulu, to effectively manage fountaingrass fuel loads. However, when applied as a single light pulse as in the present study, grazing does not appear to be an effective fuel reduction tool.

Glyphosate herbicide has been found to be an effective herbicide to kill fountaingrass and facilitate restoration of the dry forest on Hawai‘i (Cordell et al. 2002). In our study, glyphosate applied aerially was also very effective in killing fountaingrass. However, the dead grass persisted throughout the first year and the dead bunches stayed intact. While the smaller-diameter stems had broken off, a significant proportion of standing dead fine fuels remained. Although fuel continuity has been affected, these residual dead grass clumps remain available fuel and are more likely to support fire spread better than the living grasses with higher moisture content that they replaced. Additional time is needed to allow decomposition processes to take full effect. In order to reduce fire risk significantly, some sort of treatment following herbicide application should be considered. Continued application of the burning and grazing treatments is likely needed to maintain decreased fuel loading. Although glyphosate kills the currently growing plants, there is an adequate fountaingrass seed source to replace the dead plants. Different timings and orders of the treatments may also produce different results.

Fuel continuity, loading, and depth were altered by some of the fuel treatments. The fuel loadings were generally less than the fuel loadings reported by Wright et al. (2002) for fountaingrass in the same vicinity; Blackmore and Vitousek (2000) reported fuel loadings of 8 Mg/ha. As a result of the fuel treatments, the fuel bed bulk properties, such as bulk density, may have been altered. Blackmore and Vitousek (2000) reported increased bulk densities in grazed areas in contrast to ungrazed areas. The herbicide treatment appears to have altered the species composition and thus fuel particle characteristics such as surface area-to-volume ratio. We have begun to examine the impact of these fuel changes on potential fire behavior (Moraga 2006).

Economic analysis of the treatments used in this study is needed if these treatments are to be considered by private landowners as well as public agencies. The costs of the treatments and the time that fire risk is reduced needs to be determined in order to perform such an analysis. Unfortunately, the logistical constraints imposed on this study, such as additional fencing and extra personnel for the burns, the size of the plots used, and the economic data associated with this study, are not representative of operational costs. It is anticipated that actual treatment costs for both grazing and prescribed burning would be less than the costs in this study. However, it is difficult to extrapolate the costs to landscape levels from these small plots because of unknown economies of scale.

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