RESEARCH ARTICLE

CREATING HOTTER FIRES IN THE SONORAN DESERT: BUFFELGRASS PRODUCES COPIOUS FUELS AND HIGH FIRE TEMPERATURES

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ABSTRACT

Buffelgrass (*Pennisetum ciliare* [L.] Link) can create a grass-fire cycle in many parts of the world because it is a highly competitive, fire-tolerant grass and can replace less fire-tolerant native plants. Fuel loads, loss of buffelgrass biomass after herbicide treatments, and allometric data of buffelgrass growth were measured across sites in southern Arizona, USA. Prescribed fires also were conducted in buffelgrass-dominated fields to measure fire temperatures and quantify relationships between temperature and fuel load. We directly recorded temperatures up to 871 °C and indirectly recorded temperatures of 900 °C. There was no relationship between fuel load and temperature, likely because increased fuel was insufficient to contribute to additional fire intensity beyond minimum fuel loads. Compared to previously described buffelgrass stands and across different desert ecosystems, buffelgrass fuel loads were higher than reported in most other studies, and interannual variation in buffelgrass biomass

RESUMEN

El pasto buffel (*Pennisetum ciliare* [L.] Link) puede crear, en muchas partes del mundo, un ciclo de retroalimentación positiva entre el fuego y el pastizal debido a su tolerancia al mismo y a su capacidad de competir con plantas nativas menos tolerantes al fuego, llegando incluso a remplazarlas. En este estudio medimos carga de combustibles, pérdida de biomasa después de tratamientos con herbicidas y datos alométricos del crecimiento de pasto buffel a lo largo de varias ubicaciones en el sur de Arizona, en los EUA. Para realizar este estudio llevamos a cabo quemas prescritas en pastizales dominados por pasto buffel para medir la temperatura de los fuegos y cuantificar la relación entre temperatura y cargas de combustible. Medimos directamente las temperaturas hasta los 871 °C y de forma indirecta hasta los 900 °C. No se encontró una relación entre la carga de combustible y la temperatura, probablemente debido a que el incremento en el combustible fue insuficiente para contribuir a la intensidad del fuego. Las cargas de combustibles de pasto buffel fueron más altas que las reportadas en estudios previos que describen sitios dominados por pasto buffel en diferentes ecosistemas áridos. La variación in-is much lower than that of other invasive grasses, including annual and perennial grasses. As a result, buffelgrass creates a more consistent year-to-year fire hazard than annual grasses. Managers have used herbicide to reduce buffelgrass biomass and we found that, after three years of decomposition, stands of dead buffelgrass were unlikely to support fire spread. Allometric relationships can provide an accurate estimate of buffelgrass biomass of individual plants, but not fuel loads. Buffelgrass produces nonnative grasslands at relatively low elevations of the Sonoran Desert, with more biomass than comparable grasslands in more mesic environments.

teranual en la biomasa de pasto buffel fue mucho más baja que la de otras especies de pastos invasores, incluyendo especies anuales y perennes, lo que hace que el pasto buffel resulte más inflamable que otros pastos anuales. En los casos en los que se usó herbicida para reducir la biomasa de pasto buffel, encontramos que después de tres años de descomposición, es poco probable que estas comunidades sean inflamables. Las relaciones alométricas pueden dar un estimado preciso de la biomasa de plantas individuales de pasto buffel, pero no de cargas de combustibles. Este pasto produce pastizales exóticos en elevaciones relativamente bajas del desierto sonorense, con una biomasa comparable a la de pastizales que se desarrollan en ambientes más mésicos.

Keywords: *Cenchrus ciliaris*, desert grassland, fire behavior, fire temperature, grass-fire cycle, *Pennisetum ciliare*

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INTRODUCTION

Nonnative invasive species (NIS) are altering fire regimes in many parts of the world (D'Antonio and Vitousek 1992, Brooks *et al.* 2004). Changes in the fire regime caused by NIS in semi-arid and arid lands could be particularly detrimental due to long desiccating periods, high ambient temperatures, and an abundance of fire-intolerant plants. In the Sonoran Desert, the NIS buffelgrass (*Pennisetum ciliare* [L.] Link = *Cenchrus ciliaris* L.) is filling normally barren gaps between native grasses, shrubs, trees, and charismatic succulents, and then further spreads to displace native vegetation (Olsson *et al*. 2012). These bare areas formerly acted as fire breaks in low-elevation desert sites (Thomas 1991), but they currently form continuous grass stands that create fire hazards in a landscape where fires were historically rare (Wright and Bailey 1982). Buffelgrass is also causing a grass-fire cycle in other parts of the world (Miller *et al*. 2010).

The lower Sonoran Desert could be transformed by frequent, high-intensity fires to an "African" grassland (Burgess *et al.* 1991, Rutman and Dickson 2002). Fire harms many species native to the Sonoran Desert (Humphrey 1949, Rogers and Steele 1980, McLaughlin and Bowers 1982, Brown and Minnich 1986, Búrquez-Montijo *et al.* 2002). Effects of a single fire can last for decades (summarized by Abella 2009, 2010; and Rice *et al*. 2008). The iconic plant of Arizona, the saguaro cactus (*Carnegia gigantea* [Engelm.] Britton and Rose), suffers high mortality, from 68 % to 85 %, after intense fires (Rogers 1985). Cacti have numerous physiological adaptations that help them thrive in the desert, but some of these characteristics ensure low post-fire survival (Thomas 1991, 2006).

In the southwestern United States, buffelgrass has not fueled large wildfires as of this date; however, it has fueled small wildfires in urban areas of Pima County, Arizona, and along roadsides (C.J. McDonald, University of Arizona, Tucson, personal observations). Local buffelgrass populations are rapidly growing (Olsson *et al*. 2012), setting the stage for large wildland fires (Brooks and Pyke 2001). Examples of large buffelgrass-fueled wildfires and associated declines in native plants have been documented in Mexico and Australia (Búrquez-Montijo *et al.* 2002, Butler and Fairfax 2003).

Fire temperature has a significant effect on the survival of Sonoran Desert flora as it is does in other areas (Rogers 1985, Thomas 1991). Season of fire and plant physiology also affect plant damage and mortality (Wright and Bailey 1982). Buffelgrass fires in the Sonoran Desert could be exceptionally detrimental to native plants because they can occur throughout the dormant and growing seasons (May to early July and July to September, respectively) (Martin-R *et al.* 1999).

Our objectives were to: 1) measure fire behaviors, specifically fire temperature, to determine if fires fueled by buffelgrass can create intense temperatures that are both lethal to surrounding plants and higher than other North American deserts; 2) determine if the allometry of buffelgrass can be used as a simple and accurate correlate of fuel loads; and 3) determine if the dead fuel decomposes and reduces fire threats within a 3-year time period when buffelgrass fuels are managed with herbicides.

In this study, we documented fuel loads of buffelgrass at several sites in southern Arizona, USA. We also investigated the range of temperatures generated by a buffelgrass fire and assessed how fire temperature varies with weather conditions. Different ignition times (morning to late afternoon) were used as a covariate for relative humidity (RH), wind speed, and air temperature to gain an improved understanding of potential impacts of such fires on native vegetation, buildings and infrastructure, and firefighter safety. We also measured temperatures horizontally and vertically from fuels. Fire temperatures were also compared to other North American deserts.

The relationship between fuel loads and buffelgrass allometry was evaluated because allometric measures are simple to determine and traditional methods (i.e., clipping, drying, and weighing biomass) are slow, destructive, and little-used by practitioners. Lastly, to understand the rate of decomposition of fuels and how that affects potential fuel loads, the effects of herbicide application on buffelgrass fuel loads 1.5 yr and 3 yr after treatment were examined.

METHODS

All vegetation stands were sampled within the Arizona Upland Division of the Sonoran Desert (Brown 1994) in southern Arizona. We selected a field site for prescribed fires in Avra Valley, Arizona (32°15’54”N, 111°16’55”W), 30 km west of downtown Tucson, Arizona, during the summer of 2008. The City of Tucson Water Department manages this property. In the late 1970s, buffelgrass was seeded in fallow fields in Avra Valley to prevent the establishment of undesirable weeds after decades of intense agricultural use. Some native plants have recolonized the fields, including a variety of annual species, barrel cactus (*Ferocactus wizlizeni* [Engelm.] Britt. et Rose), mesquite (*Prosopis velutina* Woot.), and cholla (*Opuntia* spp.), but buffelgrass is the dominant cover.

The Avra Valley site had two burn units. The smaller burn unit was approximately 0.5 ha and contained one subplot (50 m × 50 m). The larger burn unit was divided into three 21 ha fires by fuelbreaks. Each separate fire contained five subplots (see McDonald and McPherson [2011*a*] for map of site). The subplots were located at roughly 150 m intervals in areas where fuels were relatively continuous. A total of 16 subplots (3 × 5 + 1) were created, 15 in one burn unit and 1 in the smaller burn unit. Ignition patterns ensured that all subplots were burned with a running head fire.

On 28 May 2008, the smallest burn unit was ignited at 0930. The next prescribed fire started at 1145 in the larger burn unit. The third prescribed fire began at 1255, and the last fire was ignited at 1420. All fires burned for 15 min to 30 min.

We sampled undisturbed sites with abundant buffelgrass and native vegetation in Saguaro National Park, Rincon Mountain District (SNP; 32°5'N, 110°42'36"W), 20 km east of downtown Tucson, Arizona. Although the Avra Valley site has different topography, soils, and management history than SNP, the prescribed burns were conducted in Avra Valley where containment was relatively straightforward and potential damage to native vegetation, fauna, and adjacent lands was minimized.

Buffelgrass fuel loads in SNP were evaluated in the vicinity of Freeman Homestead Trail, near Lower Tanque Verde Ridge (specifically, site 1A), and northeast of Camino Loma Alta. Sites generally had a southerly aspect with highly variable slopes (from 5 % to greater than 50 %). Sites at both Freeman Homestead and Camino Loma Alta were divided into upper and lower sections because two distinct patches (>300 m^2) of buffelgrass were present at each site.

The decomposition of herbicide-treated stands of buffelgrass was evaluated at two areas in the region: 1) near the SNP 1A site and at SNP Freeman homestead, where buffelgrass had been killed by herbicide application three years prior to our assessment, while an untreated control was left near the two treated patches; and 2) at a 2 ha site adjacent to the Quail Canyon housing community, where herbicide was applied 1.5 years before sampling. Two herbicides, glyphosate and imazapic (Roundup® and Plateau®, respectively), were applied with backpack sprayers in 2006 at the two SNP sites and glyphosate was applied in 2008 at Quail Canyon. Herbicide application rates were not recorded by previous applicators. Biomass samples were collected from all sites in summer 2009. Buffelgrass mortality approached 100 % at both treated sites, while adjacent untreated sites contained very few dead buffelgrass plants.

The Quail Canyon subdivision (32°17'17"N, 110°50'28"W) was located on an east aspect of 50 % slope 20 km northeast of downtown Tucson, Arizona. The Quail Canyon site was used only for evaluating the effects of herbicide on buffelgrass fuels. One portion of this site had been sprayed with glyphosate 1.5 years previously while another portion was untreated. There was no indication of recent fire in any of the areas we sampled.

Data Collection

We recorded data on preburn plant biomass in each burn unit in Avra Valley during May 2008, and in SNP during July 2008. Five 0.5 m^2 quadrats were randomly located within each of the 16 Avra Valley subplots and all aboveground biomass was clipped (to 2.5 cm height), dried (at 60 °C for 24 hr), and weighed (to nearest 0.1 g). Fuel loads in eight randomly located 0.5 m^2 quadrats were sampled in each site at SNP. For the herbicide-treated plots in SNP and Quail Canyon, 15 randomly located quadrats were sampled within each site using the same methods as described above.

In Avra Valley, we collected allometry data prior to the fires, on 40 randomly selected plants, 10 in each of the four burn units. Attributes quantified included: height (to top of plant), canopy diameter (leaf edge to leaf edge), and basal diameter with accuracy to 1 cm. In SNP, variation was greater than in Avra Valley, so 40 plants were used for allometric measurements at each of the five sites. All plants were then clipped, dried, and weighed. Biomass was not separated by production year, nor was standing litter removed from the samples.

To measure fire temperature, we placed ceramic indicator tiles covered in aluminum foil at 15 randomly located points within each of the 16 subplots in Avra Valley. Each indicator tile was marked with tempilstick® indicator crayons (Tempil Corporation, South Plainfield, New jersey, USA), which produce a distinct melted mark when exposed to a designated temperature. A total of 26 marks was used, ranging from 93 °C to 1260 °C on each tile, in approximately 38 °C intervals. Distance to nearest fuel load and amount of fuel was marked on the glazed side of each tile. All fuel encountered was herbaceous 1 hr timelag loads (Deeming *et al*. 1977). Tiles were placed on the soil surface with the glazed side down and the unglazed and marked side facing up, with tempilstick marks covered in foil.

To measure the vertical temperature profile, we placed tiles vertically on metal t-posts in the center of each subplot at 0 cm, 30 cm, 60 cm, 120 cm above ground with the tile face perpendicular to the ground. Tiles also were placed along gradients next to large fuel breaks and adjacent to individual barrel cactus and cholla plants. Tiles were collected after all fires were completed and the number of marks that melted was analyzed in the lab.

Covered and uncovered test tiles were placed in a muffle furnace for 1 min at 100 °C intervals from 200 °C to 900 °C to determine differences between indicated temperature and oven temperature.

Analysis

We analyzed differences in biomass within and between sites with a one-way ANOVA. Allometric differences were determined with one-way ANOVA analyses, and a multiple regression was used to explore correlations of plant allometry with biomass and fuel load. Calibrations of pyrometers in an oven were conducted with a regression analysis, and this relationship was used for tiles placed in the field. Relationships between temperatures and fuel characteristics were analyzed with regressions. A multiple regression was used to detect a correlation between fuel load, weather, and fire temperature. Separate *t*-tests were used to detect differences between herbicide treated plots and untreated plots at Quail Canyon and SNP.

RESULTS

Biomass

Pre-treatment aboveground biomass in Avra Valley was not significantly different between the four burn units (Table 1). Plots in SNP had more variable pre-treatment fuel loads than at Avra Valley due to site heterogeneity; Avra Valley was flat, and sites in SNP had varying slopes and aspects. Average biomass in Avra Valley was significantly higher than in SNP ($P < 0.001$), but fuel load did not differ between some individual plots in SNP and Avra Valley (Table 1), indicating that potential fires in SNP could exhibit the extreme fire behaviors observed in Avra Valley.

Allometry

Plant size was examined to eliminate the possibility that fuel structure among plots caused changes in fire behaviors and not fuel loads. Plants in the smaller burn unit at Avra Valley were taller and had greater basal diameter than plants in two of the larger burned subunits ($P = 0.013$ and $P = 0.049$, respectively). However, in general, plants in the three large burned subunits did not differ in size. Buffelgrass plants in SNP were, on average, nearly 30 % shorter than those in Avra Valley ($P < 0.001$) and had a smaller basal diameter than those in Avra valley ($P < 0.001$). However, basal diameter of buffelgrass plants at the Freeman Homestead Lower site and Camino Loma Alta Upper site were not significantly different from plots 1, 2, and 3 in Avra Valley, suggesting that some sites at SNP have a similar fuel structure as those in Avra Valley.

Table 1. Biomass of buffelgrass stands in Avra Valley and Saguaro National Park, Rincon Mountain District (SNP), Arizona, USA. Each strip refers to the order of the burned plots. Plots with the same letter do not differ between all entities.

Location	Biomass (g m^{-2})	Standard error	
Avra Valley burn plots			
Strip 1	1210	515	A
Strip 2	896	137	A B
Strip 3	752	150	A B C
Strip 4	671	103	A B C D
Saguaro National Park			
Camino Loma Alta Upper	685	111	A B C D
Camino Loma Alta Lower	492	96	A B C D
Freeman Homestead Lower	482	90	B C D
1A	299	61	C
Freeman Homestead Upper	260	80	D

Relationship between Allometry, Biomass, and Fuel Load

Basal diameter was strongly correlated with mass of individual plants at SNP ($P < 0.001$, $R^2 = 0.750$, R^2 adj. = 0.746, ln[mass] = 1.719[ln(basal_diameter)] + 0.180). Including both basal diameter and height proved only slightly more useful in predicting biomass ($P = 0.001$ $R^2 = 0.821$, R^2 adj. = 0.817, ln[mass] = 1.260[ln(basal_diameter)] + 1.122[ln(height)] – 3.581). Our data suggest that there is likely a positive relationship between biomass and cover of buffelgrass at the scale of the plot ($P = 0.062$); however, the predictive ability of this model is low ($R^2 = 0.41$, R^2 adj. = 0.33).

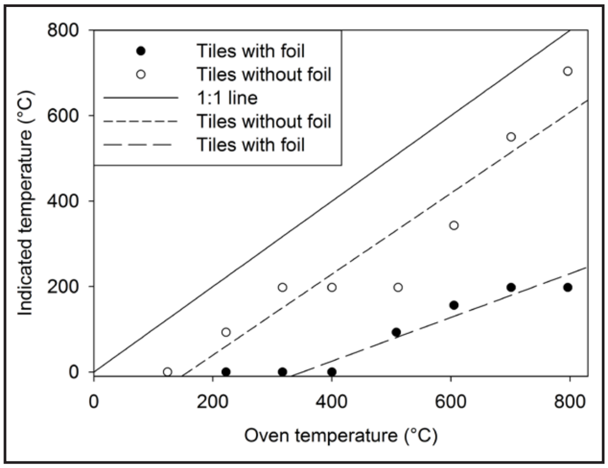

Figure 1. Regression of melting point of temperature indicating crayons by oven temperature. The 1:1 line indicates the temperature at which the marks are designed to melt.

Pyrometer Calibration Experiment: Difference between Covered and Uncovered Tiles

Uncovered tiles placed in an oven performed well, as most marks melted at their indicated temperature (Figure 1) and the slope of relationship was 0.96. A 1:1 relationship would indicate a perfect match between oven temperatures and indicator temperatures. The intercept was weakly positive (regression, $P = 0.07$), indicating a short amount of time was required before ceramic tiles heated to adequately melt the marks.

Tiles covered with foil significantly underestimated oven temperatures (Figure 1). The first tempilstik mark at 93 °C did not begin to melt until oven temperatures reached 500 °C. Upon further increases in temperature, the slope of this relationship was nearly twice as shallow as a 1:1 relationship, at 0.51 degrees per degree Celsius.

When tiles were placed in an oven at 900 °C for 1 min, the aluminum foil melted off the tile and the temperature indicated by the tempilstik mark was similar to the oven temperature. One minute is usually longer than the observed residence time of prescribed fires in grasslands. Permanent markings on the back of the tile melted and disappeared at this temperature. Many tiles collected from the field had melted foil and lost their permanent marks. If the foil was still intact, the temperature reported was based on the temperature of the highest melted mark and the regression relationship between covered and uncovered tiles shown in Figure 1. If the fire burned the foil off the pyrometer, then the temperature reported was 900 °C. If the foil was only partially burned, which occurred on 11 of 228 tiles, then we used the average of the indicated temperature and 900 °C.

Temperatures of Tiles in the Field

Maximum temperature directly recorded by indicating crayons was 871 °C. Several tiles indicated high temperatures that could be validated only in the laboratory, with estimated temperatures of 900 °C. Average temperature of all tiles was 360 °C (*n* = 228). Higher temperatures were negatively correlated with distance to fuel load (regression, $P < 0.001$), even at distances less than 1 m (regression, $P = 0.02$). Average temperature significantly increased as each fire was started later in the day (regression, $P = 0.037$; Figure 2). There was no relationship between recorded temperature

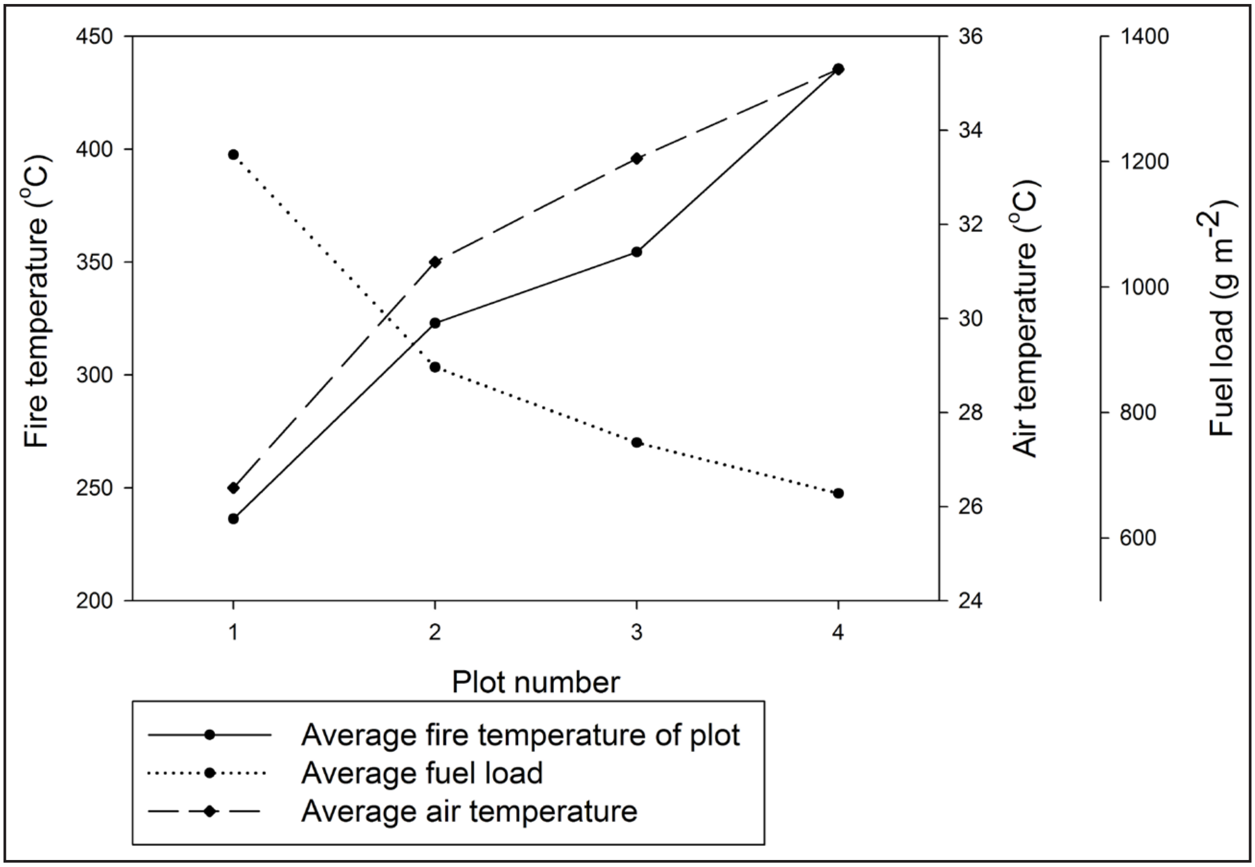

Figure 2. Average fuel load and air temperature with average fire temperature in each of four prescribed fires in Avra Valley, Arizona, USA. The axis for the fuel load data (dotted line) is given on the far right, air temperature (dashed line) is given on the right.

and direction of fuel load from the tile (regression, $P = 0.43$).

Temperatures did not differ with increased height between ground level and 120 cm aboveground (Table 2). Average temperature across all heights was 696 °C. There was a negative relationship between temperature and distance from the edge of a fuel bed (regression, $P = 0.028$; Table 2). Only two of six tiles located 120 cm from the edge of a fuel break recorded above-ambient temperatures. Average fire temperature near cactus plants was 222 °C, although 13 of 19 tiles did not indicate above-ambient temperatures due to low fuel loads.

Table 2. Relationship between heights (cm) of pyrometers affixed to t-posts, distance (cm) of pyrometer from fuel break, and average temperature (°C) during prescribed fires in Avra Valley, Arizona, USA.

	Temperature (°C)	
Height (cm)	**Vertical**	**Horizontal**
0	568	559
30	799	354
60	759	177
120	659	177

Fuel Loads and Temperatures

There was no significant relationship between the average fuel load and average fire temperature at the plot scale (multiple regression, $P = 0.42$; Figure 2). At the scale of individual tiles, placement near higher fuel loads indicated expectedly higher temperatures, with considerable variation in this pattern (regression, $P = 0.018$, R^2 adj. = 0.05).

Herbicide and Fuel Loading

Plots treated with herbicide had reduced buffelgrass biomass at both Quail Canyon and at SNP 1A and Freeman Homestead ($P = 0.055$, $P < 0.009$, and $P < 0.001$, respectively). Treated buffelgrass had 30 % less biomass 1.5 years after treatment (mean 487 g m^{-2} vs. 342 g m^{-2}), and 3 years after treatment there was 55 % less biomass (299 g m^{-2} vs. 132 g m^{-2}) at 1A, and 70 % less biomass at Freeman homestead (864 g m^{-2} vs. 277 g m^{-2}) (Figure 3). In addition, buffelgrass fuel loads were discontinuous on both of the three-year degradation plots at SNP.

DISCUSSION

We recorded peak fire temperatures of 871 °C and 900 C in buffelgrass-fueled fires. Temperatures during the peak fire season (June to July) likely are higher than what we observed because we burned under relatively cool conditions in May. Summer high temperatures in the area average 38 °C, whereas our prescribed fires occurred at temperatures between 27 °C and 34 °C.

Similarly, high peak temperatures were found in a variety of ecosystems. In grasslands of southeastern Australia, peak fire temperatures were 467 °C with 150 g m^{-2} of fuel and 523 °C with 1100 g m^{-2} of fuel (Morgan 1999), compared to 793 g m^{-2} (mean) in our study. In a location comparable to this study, a mesquite-acacia shrubland, peak fire temperature was 700 °C when air temperatures were high (39 °C) and fuel loads were low (120 g m^{-2}) (Streeks *et al.* 2005). In mesquite grasslands in northwest Texas, peak temperatures of 680 °C with 785 g m^{-2} of fuel were recorded and declined to 83 °C with 170 g m^{-2} of fuel (Stinson and Wright 1969). Maximum temperatures at 1 cm above ground level ranged from 90 °C to 400 °C in the Sonoran Desert where fuel loads ranged from 70 g m^{-2} to 320 g m^{-2} (Patten and Cave 1984). Given the high variation between fire temperature and fuel loads, buffelgrass fire temperatures could be higher than reported here, with even greater effects on plants and soils (Adams *et al.* 1970, Cave and Patten 1984).

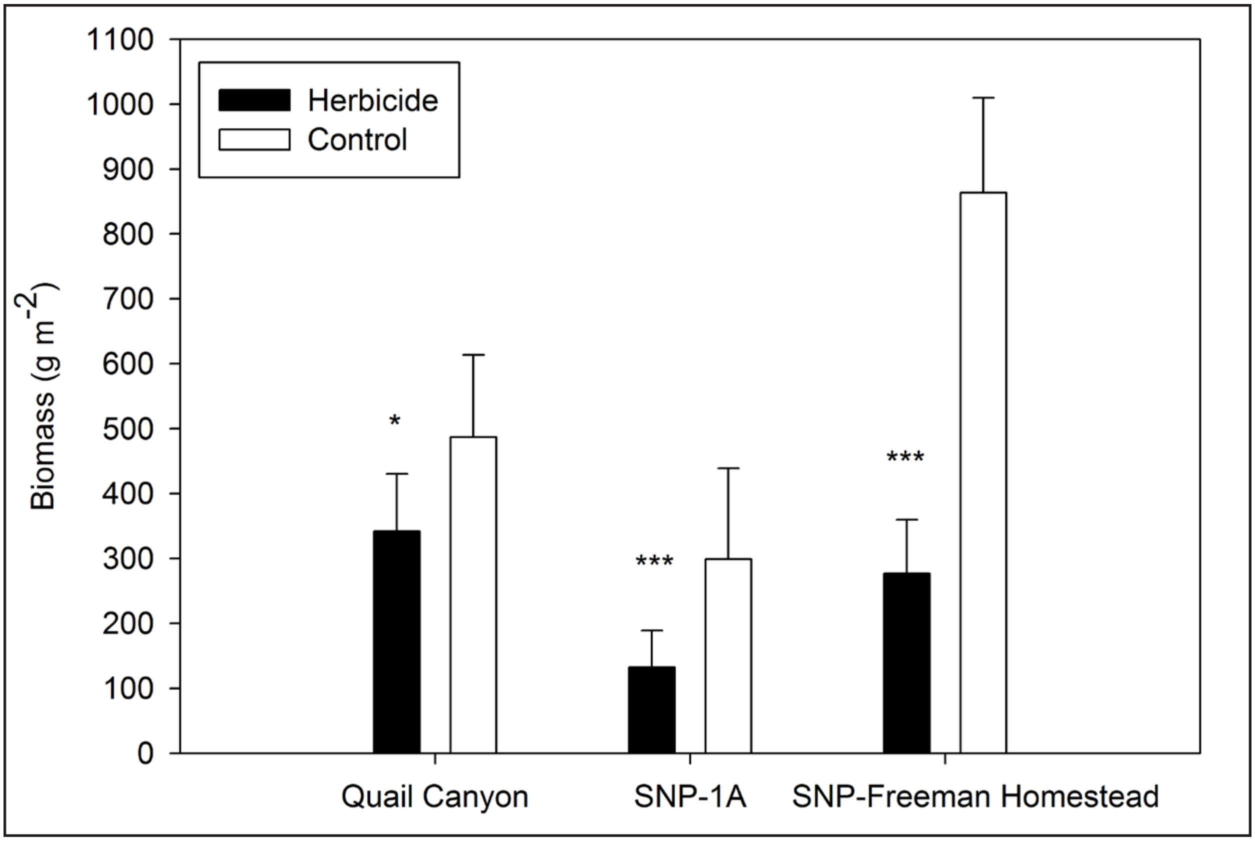

Figure 3. Degradation of buffelgrass biomass following herbicide treatments. Plots were located in Saguaro National Park and the Quail Canyon neighborhood in Tucson, Arizona, USA. The plots in Quail Canyon were treated 1.5 years previously, while both plots in SNP were treated three years previously. Single asterisk (*) indicates a significant difference between treated and untreated plots at each site of $P = 0.055$; triple asterisks (***) indicate a significant difference of $P < 0.001$. Error bars indicate 95% confidence intervals.

Aboveground biomass of buffelgrass plots was also higher than observed in previous studies. In Mexico, buffelgrass fuel loads ranged from 300 g m^{-2} to nearly 500 g m^{-2} (Mayeux and Hamilton 1983; Martin-R *et al.* 1995, 1999). In other parts of SNP, fuel loads were 250 g m^{-2} to 280 g m^{-2} (Esque *et al*. 2007). Our fuel loads were mostly comparable to those found in Australia, ranging from 300 g m^{-2} to 1200 g m^{-2}, where precipitation is nearly double that of Tucson (Jackson 2005). It is unknown if the high fuel loads observed in this study are a function of the climate in southern Arizona, or because buffelgrass is becoming more dense as the time since invasion increases, or both.

Buffelgrass fuel loads were comparable to or greater than fuel loads in nearby semi-arid grasslands not dominated by buffelgrass, despite those semi-arid grasslands receiving more rainfall and experiencing cooler summer temperatures than the lower Sonoran Desert (Brown 1994). Fuel loads of grasslands dominated by the nonnative Lehmann lovegrass (*Eragrostis lehmanniana* Nees) range from 110 g m^{-2} (Cable 1976) up to 600 g m^{-2} (Cox *et al*. 1990). McDonald and McPherson (2011*b*) reported values intermediate between these two studies for semi-arid grasslands dominated by Lehmann lovegrass. Buffelgrass fuel loads exceeded even peak standing crop biomass in native big sacaton (*Sporobolus wrightii* Munro ex Scribn.) grasslands in Arizona, which ranged from 390 g m^{-2} to 515 g m^{-2} (Cox 1985). The amount of fuel sufficient to carry a fire in the Sonoran Desert is four times lower than our most sparse buffelgrass plot with 69 g m^{-2} of annuals and litter (Patten and Cave 1984), and 67 g m^{-2} of mixed perennial and annual grasses (Wright 1980).

Buffelgrass production was also higher than other nonnative annual grasses in the southwestern US. In the Mojave Desert fuel loads (including Mediterranean grass, *Schismus* spp., and red brome, *Bromus rubens* L.) ranged from 6 g m^{-2} to 140 g m^{-2} (Brooks and Berry 2006) and up to 210 g m^{-2} (Brooks 2000). Fuel loads of 25 g m^{-2} to 125 g m^{-2} in the Mojave Desert helped create peak fire temperatures of 200 °C (Brooks 2002). In sagebrush (*Artemesia* spp.) communities in the Great Basin, cheatgrass (*Bromus tectorum* L.) production is also highly variable, ranging from 40 g m^{-2} (Hull and Pechanec 1947) to nearly 400 g m^{-2} (Klemmedson and Smith 1964). Variation also was affected by disturbance history, with production of *Bromus* spp. in Mojave and Great Basin deserts ranging from 0 g m^{-2} to 62 g m^{-2} on undisturbed sites, while burned sites had 6 g m^{-2} to 75 g m^{-2} (Beatley 1969). In the Sonoran Desert, wide variation was observed in the production of annuals (including nonnatives) ranging from 9 g m^{-2} to 95 g m^{-2} (Patten 1978).

Herbicide is effective at reducing fuel loads, and we found that after three years of post-treatment degradation, buffelgrass fuel loads were discontinuous and low. It appears that this treatment effort and three-year degradation period is moving fuel loads towards those of more fire-resistant landscapes common in the Sonoran Desert.

Fire temperatures were much higher than ambient temperatures at both 1.2 m above ground level and 1.2 m away from a fuel break. Radiant heat flux from a fire is one of the principal factors in determining ignition of a structure (Cohen and Butler 1998). Also, in these experimental fires, observers were repeatedly forced to back away from the flames to take photographs or record fire behavior because of a high radiant heat load and long flame lengths, even though observers were located in fuel breaks where temperatures were lower compared to the fuel beds. Common fuel breaks in rural areas (i.e., trails, unpaved roads, rocky slopes) are likely not sufficient to contain buffelgrass fires.

Allometric measurements were useful to estimate biomass of individual plants but not fuel loads over a given area. Furthermore, fuel load was not a useful predictor of fire temperature at the plot scale. Fire intensity is determined by the interaction between weather and fuel load, but weather can be a strong determinant of fire intensity (Bessie and Johnson 1995). Apparently even the minimum fuel loads we observed did not constrain high fire temperatures.

Our data support the contention of Wally *et al.* (2006) that ceramic tiles underestimate actual temperatures. Calibrations can significantly improve the functioning of ceramic tiles, and pyrometers have advantages over the more accurate, but also more expensive, recording thermocouples. In particular, very large numbers of ceramic tiles can be placed quickly and easily in scattered locations throughout a large fire.

Buffelgrass fires will be more intense and detrimental to native flora and fauna than fires in many other arid and semi-arid ecosystems in southwestern North America. Nonnative grasses in the Great Basin and Mojave deserts are annuals that are short and have a small basal diameter, thus production values are much lower than buffelgrass. Managers in those ecosystems are certainly aware of the effects of these species (Brooks and Matchett 2006, Rice *et al.* 2008), and our data supports what managers and researchers have observed: buffelgrass fuel loads fluctuate less than invasive annuals, which creates a more consistent fire hazard.

Buffelgrass produces high fuel loads, and high ambient temperatures can produce high peak fire temperatures, greater than in many other comparable ecosystems. Our results suggest that, above a minimum fuel load, buffelgrass fire behaviors will correlate more with weather than fuel load, thus even thin but continuous patches of buffelgrass can produce fire temperatures that are lethal to native plants. Managers can avoid these impacts by reducing fuel loads with application of herbicides, breaking the continuity of buffelgrass fuels. A highly effective herbicide treatment and three years of degradation appears to place these plant communities on a trajectory to resemble the fire-resistant landscapes of the Sonoran Desert. Alternatively, if practitioners cannot wait three years, managers could treat buffelgrass with herbicides, wait several weeks, and then physically remove nearly all fuels to quickly create a discontinuous fuel bed that should not resprout. Further research is necessary to confirm these predictions.

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