Journal of Arid Environments 75 (2011) 1147–1154

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Fire behavior characteristics of buffelgrass-fueled fires and native plant community composition in invaded patches

C.J. McDonald [a,*], G.R. McPherson [a,b]

[a] School of Natural Resources and the Environment, University of Arizona, Tucson, AZ 85721, USA
[b] Department of Ecology and Evolutionary Biology, University of Arizona, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 17 April 2010
Received in revised form
8 December 2010
Accepted 15 April 2011
Available online 12 May 2011

Keywords:
Pennisetum ciliare
Cenchrus ciliaris
Grass/fire cycle
Sonoran desert
Species richness
Fuel model

ABSTRACT

Buffelgrass invasions have been documented in Australia to North America, pointing to an end result of large-scale wildfires. In heavily populated areas such as Nogales, Sonora and Tucson and Phoenix, Arizona buffelgrass populations are growing exponentially. Although much research has been conducted on buffelgrass, relatively little is known about fire behaviors produced by a buffelgrass-fueled fire. To determine which abiotic and biotic characteristics best predict fire behavior, fire-behavior characteristics were measured in four prescribed fires in southern Arizona. Given that buffelgrass is known to decrease native plant richness in other ecosystems, the relationship between buffelgrass abundance and native plant cover was evaluated. Buffelgrass fires are more intense than fires in surrounding ecosystems, even in communities with comparable fuels. There is a strong negative relationship between buffelgrass cover and native plant cover. In addition, buffelgrass appears to be invading favorable microsites rather than species-poor communities and is radiating from the former sites. Historically, fire was rare in arid regions, but with the increase in fuels and because arid regions have weather that promotes intense fire behavior, as observed in this study, managers will increasingly observe and need to mitigate hazardous fires.

1. Introduction

A significant amount of work has been conducted previously on altered fire regimes and invasive species (D'Antonio and Vitousek, 1992; Zouhar et al., 2008). Buffelgrass (*Pennisetum ciliare* (L.) Link = *Cenchrus ciliaris* L.), an invasive grass native from Africa to Southern Asia, is dominating undisturbed habitats and altering the grass/fire cycle in diverse habitats in Australia (Butler and Fairfax, 2003; Clarke et al., 2005; Low, 1997), Mexico (Arriaga et al., 2004; West and Nabhan, 2002), Texas (Tjelmeland et al., 2008), and Arizona (Burgess et al., 1991; Esque et al., 2004). Buffelgrass fits the grass/fire model well: In the Sonoran Desert of southwestern North America, it is invading areas with relatively sparse continuous fuels where fire is nearly absent and native plants and animals have few adaptations to survive fire (Esque and Schwalbe, 2002; Humphrey, 1974; Rogers, 1986), thereby transforming fire-resistant deserts into fire-prone grasslands (Búrquez-Montijo et al., 2002). Buffelgrass, a C_4 grass, is invading Sonoran Desert communities dominated by C_3 and CAM plants, giving buffelgrass a competitive advantage, by having a higher growth rate during the summer growing season (Gibson, 1996). Also, the extent of buffelgrass is increasing exponentially (J. Betancourt unpub. data, P. Grissom unpub. data).

Fire negatively affects the majority of plants in the Sonoran Desert (Cable, 1965, 1967; McLaughlin and Bowers, 1982; Rogers, 1985; Rogers and Steele, 1980; Wilson et al., 1995; Wright, 1980). Even if fire does not directly kill plants, those plants, especially cacti that survive a fire, will have a faster and higher mortality than unburned plants (Bunting et al., 1980; Humphrey, 1974; Thomas, 2006). In contrast, buffelgrass is fire tolerant and often increases in abundance after fire (Butler and Fairfax, 2003; Martin-R et al., 1999).

It is reported that buffelgrass burns at "very hot" temperatures (Cohn, 2005), but relatively little is known about the fire behaviors produced from a buffelgrass-fueled fire, especially during the historical fire season of the Sonoran Desert, June–July (McPherson, 1995). In this study prescribed fire is used to measure the range of fire behaviors in a buffelgrass-dominated desert in southern Arizona. The biotic and abiotic factors that best predict fire behaviors during buffelgrass fires are also investigated.

It is currently unknown which fuel model best describes buffelgrass. In the United States, there are 53 models used to classify natural vegetation for fire behavior fuel models (Anderson, 1982;

* Corresponding author. Present address: University of California, Cooperative Extension, 777 East Rialto, San Bernardino, CA 92415, USA. Tel.: +1 909 387 2242; fax: +1 909 387 0730.
E-mail address: cjmcdonald@ucdavis.edu (C.J. McDonald).

0140-1963/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jaridenv.2011.04.024

Scott and Burgan, 2005). Buffelgrass produces higher fuel loads than Australian fire behavior models can accommodate (Simmons et al., 2006). Fire behaviors were observed during prescribed fires to determine which fuel models might be appropriate to classify a buffelgrass-fueled fire. Land managers and fire fighters use fuel models when estimating fire behaviors, fire hazard and/or fire suppression tactics. For example, fire management plans are created and used by managers where appropriate fuel models aid in determining pre-attack plans, suppression tactics, appropriate safety tactics, inventorying pre-suppression resources, and determining the likelihood of fire occurrence based on fuel model (USDI, 2007).

The objectives of this study are to determine the fire-behavior characteristics of a buffelgrass-fueled fire and match those behaviors to a fuel model, to measure the plant community composition in areas invaded with buffelgrass, and to determine the fire-induced effects on native plants based on the behavior of buffelgrass-fueled fires. A site representative of a typical buffelgrass invasion was located. Due to safety and conservation issues prescribed fires could not be conducted at this site, where buffelgrass fuel loads were high and long-lived native plants were relatively abundant. Prescribed fires were moved to an area where long-lived native plants were less numerous, but containment was more straightforward. Plant community and fuel characteristics between the two sites were compared to determine if observed fire behaviors at the burned site would be expected at the unburned site where native species conservation is paramount.

2. Materials and methods

2.1. Study area

The study areas were in and near the city of Tucson, Arizona. Vegetation is classified as Arizona Upland Division of the Sonoran Desert (Brown, 1994) that has been invaded by buffelgrass. There is a varying amount of native vegetation remaining on the two selected field sites, Avra Valley and Saguaro National Park, Rincon Mountain District (SNP). Locations with abundant buffelgrass and native vegetation were located at SNP (lat. 32.15, long. −110.71). Due to safety concerns and damage to numerous native plants, including the namesake species of Saguaro National Park (*Carnegiea gigantea* (Engelm.) Britton and Rose), prescribed fires could not be conducted in SNP and were instead conducted in nearby Avra Valley.

An appropriate field site was selected for four prescribed fires in Avra Valley (lat. 32.265, 1ong. −111.282) during summer 2008. The site has fewer long-lived native plants and containment of a prescribed fire was more manageable at this site. The site is a former agricultural field managed by the City of Tucson and was dominated by buffelgrass with occasional mesquite (*Prosopis velutina* Woot.) trees. Four prescribed fires were conducted, one in a 0.5-ha square and 3 in approximately 800-m long and 250-m wide (21 ha) rectangles, oriented east to west (Fig. 1).

To quantify fuel loads in stands of buffelgrass where it had invaded native vegetation, five plots were sampled in the west side of SNP. Sampling locations were identified by park employees as having spatially continuous buffelgrass cover within a 2-h hike from roads.

The Avra Valley site has different topography, soils, and land-use history than sites at SNP, but prescribed burns were conducted in Avra Valley to prevent damage to native vegetation and fauna on SNP and adjacent private lands. All sites had spatially continuous cover of buffelgrass and fuel loads.

2.2. Data collection

Data on plant community composition and fire behavior were collected in five 50- by 50-m subplots inside each 21-ha plot (Fig. 1).

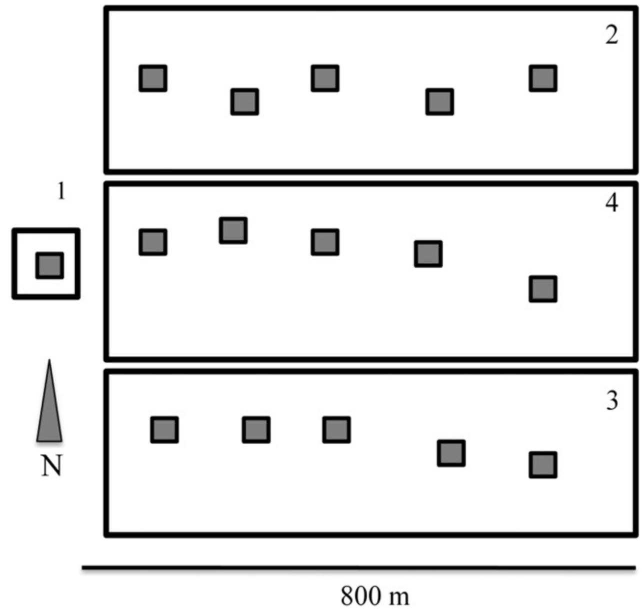

Fig. 1. Map of plots where 4 prescribed fires were conducted in Avra Valley, Arizona. Small shaded squares indicate sampling subplots. Numbers indicate firing order.

The subplots were not randomly located, but located in areas where buffelgrass fuel loads were consistent and mesquite cover was low, thus creating uniform fire behavior. Each subplot was located at an approximately 150-m interval to sample across each strip in a systematic manner. A total of 16 subplots were used, including the single subplot from the 1st and smallest fire (Fig. 1). A census of cacti was completed after burning, because many cacti could not be located before the fires in the deep buffelgrass field.

Plant cover was estimated using the point-intercept method. Within each subplot, six transects were randomly located and oriented north to south. In each transect, plants were identified at 50 points spaced 0.5 m apart, thus transects were 25 m in length. To include those plants that contributed the most to fire behavior and formed a consistently continuous fuel bed, only plants shorter than 1.5 m were recorded. Thus mesquite was precluded as it can confound observations of fire behavior. Post-fire community composition was recorded in a similar manner except black and white ash and burned stubble 2.5 and 5 cm tall were added. The addition of the post-fire stubble allowed measurement of burn severity in a manner similar to standardized methods (USDI, 2003), with the exception that the scorched category (burn severity 4) was eliminated.

Preburn plant biomass was estimated in each subplot during May. All aboveground biomass was clipped, dried (at 60 °C for 24 h) and weighed (to nearest 0.1 g) in five 0.5-m^2 quadrats randomly located in each of the 16 subplots.

Plant community composition was described for buffelgrass patches inside SNP. Data collection matched those methods in Avra Valley, with the exception that in several buffelgrass patches subplot size was reduced from the standard 50 × 50 m to fit the buffelgrass patch. If a starting point for a transect fell outside of a patch of buffelgrass it was moved to the nearest edge of the population and continued inside the patch. Five buffelgrass patches in SNP were located in the vicinity of Freeman Homestead Trail, near Lower Tanque Verde Ridge (specifically site “1A”), and northeast of Camino Loma Alta.

Fuel-moisture content (FMC) samples were collected from several individual plants in each sample, each at 0915, 1015 and 1520 the day the four prescribed fires were conducted. These nine samples were collected from the interior of each prescribed-fire plot or nearby representative fuels. Most samples were composed of dead cured fuel; one sample included live green fuel mixed with dead fuel. All aboveground growth was collected in each sample, and live and cured fuels were collected and measured together.

Fire crews collected weather data every 15 min for the duration of the fires. Measurements of wind speed, wind direction, wind gusts, relative humidity, temperature and dew point were obtained (USDI, 2003). Fine fuel (dead, cured grass) moisture (Fine Dead Fuel Moisture, FDFM) content was calculated from weather observations taken on site (Schroeder and Buck, 1970). All burns were conducted on flat ground with no aspect at approximately 650 m elevation.

Fire rate of spread (ROS) was estimated with wooden stakes placed in a straight line in each subplot at 10-m intervals spanning a length of 50 m. Observers were stationed along the north and south side of each subplot to maximize viewing opportunities and record the time the fire passed from stake to stake. When observers recorded the ROS on the same stakes (9 out of 32 samples) an average between the two values was used. We present data based on the best match between the stakes and wind direction and omit data when the stakes and wind were close to perpendicular.

Residence time of fires was determined from video footage obtained during the fires. A nearby stationary object (tree or t-post) was used in each video to time how long it took the entire flaming front to pass by the object.

Flame lengths (FL) were measured using pictures taken during each fire. The average and peak FL were recorded using standard reference points (i.e. people, t-posts, buffelgrass height), for each picture and plot. The peak FL was measured as the longest of any flame in each picture (excluding fire whirls), whereas the average FL was the average heights of all flames in a picture, both incorporated the effects of wind when necessary.

Percent of post-fire damaged tissue was estimated on cacti throughout the site. Two observers independently estimated damage and an average value was recorded. Tissue was counted as damaged if the epidermis was charred or blistered or if photosynthetic tissue was light green, yellow or not of a firm texture. In general, only cacti large enough to survive extreme temperatures remained; cacti that were thin and short (i.e. *Opuntia* spp. $<$ 15 cm tall) were almost completely consumed by the fires. Cactus height, diameter and nearest fuel load were measured after treatment.

Observed fire behavior was used to validate the effectiveness of several fuel models in the program BEHAVE 4.0 (Andrews et al., 2008). BEHAVE is used to predict fire behavior and validate fuel models for managers, fire fighters and researchers. Fuel models were tested in BEHAVE to compare predicted fire behavior to observed behaviors (Anderson, 1982; Scott and Burgan, 2005).

2.3. Analysis

Fuel loads in Avra Valley and SNP were analyzed with separate ANOVA. Fire behavior characteristics were analyzed with a variety of methods. ROS was only compared between the last two fires due to low samples sizes in the earlier two fires and differences between fires were analyzed with an ANOVA. The relationship between individual ROS values and wind speed was identified with a regression. Flame lengths were analyzed with a Welch ANOVA due to different sample sizes. Fire behavior correlations with weather variables were conducted with a regression.

Plant community data in Avra Valley and SNP were analyzed with ANOVA analyses. A regression was used to determine the relationship between buffelgrass cover and native plant cover. Relative plant cover is defined as the proportion of cover for each plant group by cover of all plants. Differences in post-fire plant cover were analyzed with ANOVA. A Principal Component Analysis (PCA) ordination was calculated for the plant community using the variance/co-variance matrix. Last, damage to cacti and correlations with plant characteristics were analyzed with a regression.

3. Results

On 5/28/08 four prescribed fires were completed throughout the day to incorporate variation in diurnal weather (Table 1). One of the four fires was completed in one 800 m long headfire at an average rate of spread (ROS) of 0.67 ms^{-1}. All other fires were ignited around each subplot, at 250 m in length, and fires appeared to achieve a steady ROS within a few seconds (see Cheney and Gould, 1995).

3.1. Fuel moisture

The landowner sprayed a majority of the Avra Valley site with herbicide the summer before the fire, so measured fuel moisture content (FMC) was low and most plants were dead. FMC of dead plants ranged from 3.6 to 11.1%, with an average moisture of 7.4%. The FMC of plants with some living material was 24.6%.

3.2. Fuel load

Average fuel loads were 793 g/m^2 and biomass in Avra Valley did not differ between the four fires ($p = 0.25$, Table 1). Fuel loads in SNP are given in Table 2. Similarities exist in fuel loads between Avra Valley and SNP; only one of five plots in SNP had significantly different ($p < 0.05$) fuel loads compared to all Avra Valley plots.

3.3. Fire behavior

Rate of spread (ROS) at individual plots was positively correlated with wind speed ($p = 0.0007$) and was likely fastest in the last fire of the day ($p = 0.053$), but due to low sample sizes statistical analysis was only possible between the last two fires. At individual plots forward ROS was variable ranging from 0.40 to 2.34 ms^{-1} (Table 1). The lowest observation of ROS was omitted as an outlier, likely due to an error in data collection.

Residence time of fires ranged from 30 to 40 s when winds were calm in the morning and shortened to 20–30 s when winds were stronger in the late afternoon.

There were significant differences in average and peak flame length's (FL) between plots ($p = 0.046$ and $p = 0.021$, respectively).

Table 1
Weather, fuel, fire behavior and percent buffelgrass cover data for four prescribed fires conducted in Avra Valley, AZ on 5/28/08. Letters denote significant differences ($p < 0.05$). Abbreviations: FDFM- Fine Dead Fuel Moisture, FMC-Fuel Moisture Content, ROS- Rate of Spread, FL- Flame Length, BG- buffelgrass.

	Fire							
	1		2		3		4	
Time Start	0930		1145		1255		1420	
Time End	0945		1205		1325		1455	
Air Temp	27		30		32		34	
Wind (km/h)	1.6–4		0–6.4		3.2–6.4		3.2–14.5	
Gusts (km/h)	12.9		0		14.5		27.4	
RH (%)	29		29		21		18	
FDFM	7		4.5		4		2	
FMC	6.7		5.9				9.5	
Fuel Load (gm^{-2})	1211		896		752		671	
ROS (ms^{-1})	0.79		0.72		0.64	A	1.34	B
FL Avg (m)	3.4	A	2.4	B	2.6	B	3	AB
FL Peak (m)	5.4	A	3.9	B	3.7	B	4.4	AB
FL Back (m)	1.8		1.3		1.9		2	
% BG Cover	78.7		51.3		57.7		50.8	

Table 2
Fuel loads and percent buffelgrass cover in plots across Saguaro National Park (SNP), Rincon Mountain District near Tucson, AZ. Letters indicate significant differences ($p < 0.05$). Sites are Camino Loma Alta Upper and Lower (CLAU and CLAL, respectively), 1A and Freemen Homestead Upper and Lower (FHU and FHL, respectively).

	gm^{-2}			% cover
CLAU	685	A		83
CLAL	492	A	B	57
FHL	482	A	B	49
SNP Mean	381			52
1A	299		B	48
FHU	260		B	25

FL of headfires was 1–5 m, with averages listed in Table 1. The tallest peak FL that was not a fire whirl was 7.5 m. Backing fires were possibly different between subunits ($p = 0.07$). Several fire whirls, one up to 28 m tall, were observed when winds were light and variable. The most common burn severity class was moderately burned, followed by heavily burned and bare ground was encountered more than any burn severity class (Fig. 2). ROS and FL samples differed between plots (from 1–19 and 18–43, respectively), so caution should be used when interpreting these results.

3.4. Fire behavior correlations

ROS and FL were positively correlated with wind speed (Fig. 3, $p = 0.041$ and 0.023, respectively) and not significantly correlated with air temperature, fuel load, relative humidity (RH), fuel moisture content (FMC) or fine dead fuel moisture (FDFM). Due to differences in sampling techniques between weather and fire behavior data, these fire behavior correlations were conducted at the plot scale, where $n = 4$.

3.5. Plant community composition

Over the entire Avra Valley site 26 species of plants were found. Half of all species were winter annuals. Pre-burn richness in the four plots ranged from an average of 9–12 species and was not significantly different ($p = 0.14$).

The majority of species found in Avra Valley were rare. The combined cover of all plant species, excluding buffelgrass, was between 11 and 36% of relative plant cover on any single plot. Furthermore, only five taxa (*Descurainia pinnata* (Walter) Britton, *Sisymbrium irio* L., *Cryptantha* spp., *Mentzelia* spp. and *Amsinckia menziesii* (Lehm.) A. Nelson and J.F. Macbr. var. *intermedia* (Fisch. and C.A. Mey.) Ganders) had total cover greater than 3% on any one of the 16 subplots. Besides buffelgrass the next most abundant non-native species was *S. irio* with an average cover of 2.2%. The most abundant perennial plant, excluding buffelgrass, was the subshrub *Isocoma tenuisecta* Greene, which occupied an average of 0.6% cover. Table 3 shows the average relative cover for physiognomic groups for SNP and Avra Valley, and before and after prescribed fires.

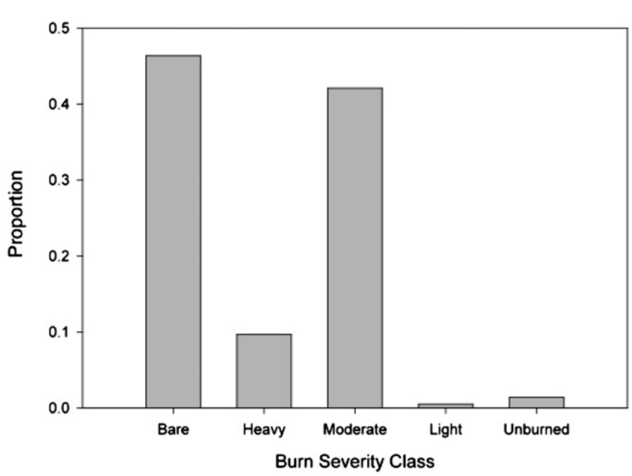

Fig. 2. Average proportion of burn severity condition classes of four prescribed fires in a semi-arid grassland in Avra Valley, Arizona. Severity class "scorched" was not used in this study.

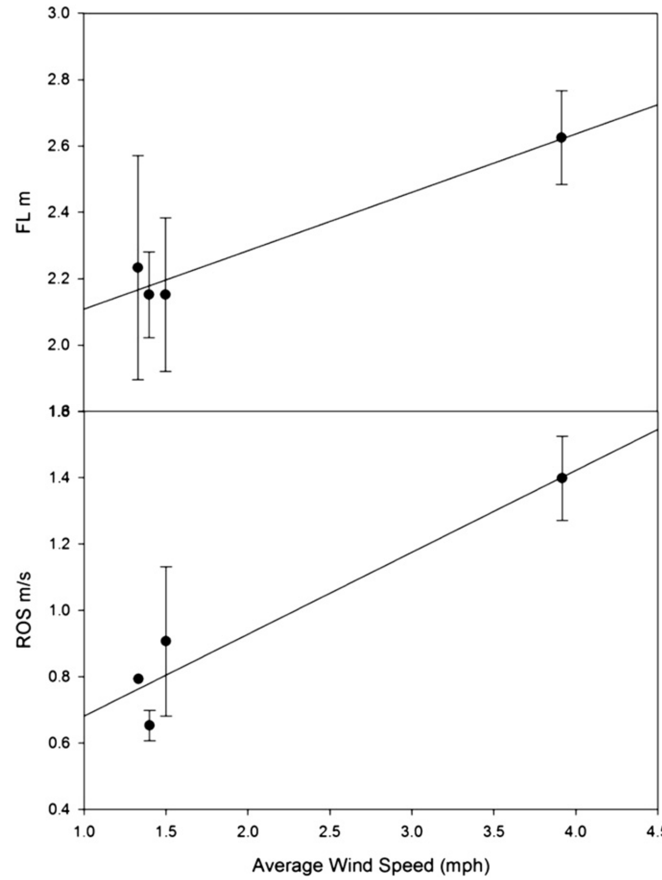

Fig. 3. Top: relationship between flame length (FL) and wind speed. Bottom: relationship between rate of spread (ROS) and wind speed for four prescribed fires conducted in Avra Valley, AZ in May 2008. Regression lines for ROS and FL were calculated from each of four prescribed fires ($n = 4$). Samples used to calculate 95% confidence intervals ranged from 1–30.

In SNP 26 species were found in buffelgrass patches, the same number as Avra Valley. Many of these species in SNP were perennial shrubs as opposed to winter annuals in Avra Valley (Table 3). The common native plants found in SNP were the perennial shrubs *Encelia farinosa* A. Gray ex Torr. (4.1%), *Acacia greggii* A. Gray and *Jatropha cardiophylla* (Torr.) Müll. Arg. (both at 2.5%) and the perennial vine *Janusia gracilis* A. Gray (0.6%). Richness across each site ranged from 6 to 12 species; however, average richness between Avra Valley and SNP was not significantly different ($p = 0.39$, means = 9.4 vs. 10.6 species, respectively). Besides buffelgrass the only other non-native species found in SNP was the perennial Lehmann lovegrass (*Eragrostis lehmanniana* Nees), which covered 2% of a single plot.

There is a negative relationship between species richness and buffelgrass cover in SNP ($p < 0.0001$, Fig. 4). Furthermore, richness was markedly low at some sites when buffelgrass cover was only 40% (Fig. 4). A negative relationship between buffelgrass cover and

Table 3
Percent cover by functional group of plots infested with buffelgrass at Saguaro National Park, at plots in Avra Valley before prescribed fires and at the same plots in Avra Valley after prescribed fires. Column totals do not add to 100 due to omission of several rare groups and rounding error.

	SNP	Avra Valley	
		Pre-Fire	Post-Fire
Buffelgrass	52.5	59.6	0.0
Bare	10.3	15.7	46.4
Litter	8.5	10.7	1.3
Rock	12.1	0.0	0.0
Shrubs	11.7	0.6	0.0
Annuals	0.0	11.1	0.2
Succulents	1.8	0.0	0.0
Ash	0.0	0.0	50.4
Stubble	0.0	0.0	1.8

native plant cover ($p < 0.0001$, Fig. 5) was also observed. Rutman and Dickson (2002) provide similar data for buffelgrass cover and native plant cover. We analyzed their data and found no relationship between buffelgrass cover and native plant cover ($p = 0.89$). However, only two plots out of 17 in their study had a cover of buffelgrass higher than 5%. The cover of buffelgrass in SNP was on average 16 times higher than observed in the Rutman and Dickson (2002) study.

Before the fires, plots were strongly dominated by buffelgrass, with total cover averaging 60% (Table 3) and even though buffelgrass occupied a minority of absolute cover on several plots in SNP, it was always a large majority of relative plant cover in SNP and Avra Valley. Although the range of buffelgrass cover in SNP (Table 2) was wider than in Avra Valley, the cover of bare ground, litter and rock was also higher in SNP. Thus relative plant cover occupied by buffelgrass was similar between the two sites: 71–95% at SNP and 74–90% at Avra Valley.

All the prescribed fires in Avra Valley consumed nearly 100% of the herbaceous fuel. Species richness was reduced by 80% due to the fires. Only five species of plants were found after the fires, compared to 26 before, and those five species occupied only 0.2% cover. The cover of burned material (ash and stubble) was similar to the preburn cover of buffelgrass (Table 4). The cover of burned material did not differ among the four plots ($p = 0.19$).

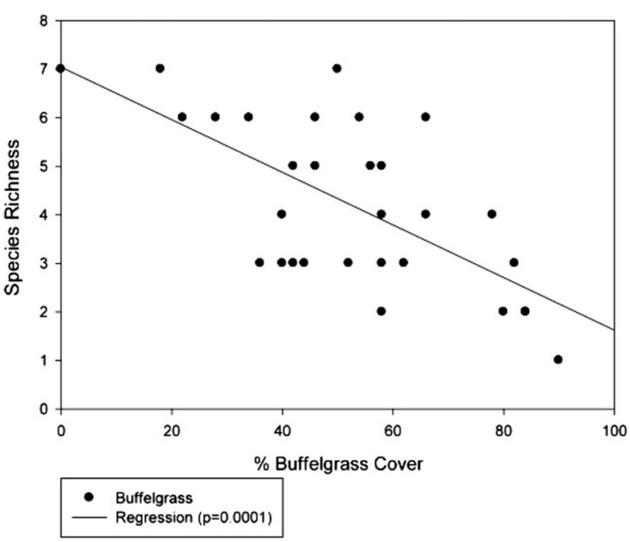

Fig. 4. Cover of buffelgrass at five sites in Saguaro National Park, Rincon Mountain District (SNP) and the relationship to species richness ($p = 0.0001$).

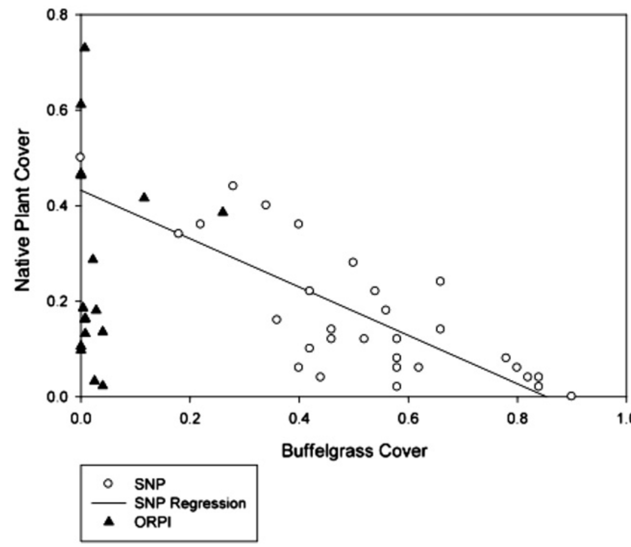

Fig. 5. Cover of native plants and buffelgrass at Saguaro National Park (open circles) and at Organ Pipe Cactus National Monument (triangles, ORPI). Regression analysis indicates a negative relationship at SNP ($p < 0.0001$) but no relationship at ORPI ($p = 0.89$, not shown).

Principal component analysis (PCA) ordination indicated the strong effect of fire on plant species composition (Fig. 6). The two sites overlapped in ordination space before burning, as expected in areas with high cover of buffelgrass and low cover of native plants. Two PCA axes explained 96% of variance. The first axis corresponds to buffelgrass cover and bare ground, separating burned and unburned plots. The second axis corresponds with cover of rock and cover of several species of native plants (*Jatropha cardiophylla*, *Acacia gregii* and *Janusia gracilis*) where plots with the most native plants are at low values of axis 2.

3.6. Damaged cacti

Of the 147 cactus plants observed post-fire, 82% were found in the third plot. Barrel cactus (*Ferocactus wislizeni* (Engelm.) Britton & Rose) dominated, with 91 plants, and the only other genus present was cholla (*Opuntia* spp.), with 56 individuals. Eighty-nine percent of tissue was damaged immediately after fires, a value that was not correlated with the species ($p = 0.32$), or size of cactus plants ($p = 0.99$ height; $p = 0.10$ width). Cholla ranged up to 230 cm tall and 348 cm wide and the largest barrel cactus plants were 78 cm wide and 98 cm tall. Mortality directly related to the fire was not determined because secondary sources, notably ground squirrels, further damaged many burned cacti.

Table 4
Average differences between four fuel model predictions of fire behavior using BEHAVE and observed values during prescribed fires. Negative differences represent an underestimate of observed values, positive differences represent an overestimate.

	6.4 km/h Wind % Difference		14.5 km/h Wind % Difference	
	ROS	Peak FL	ROS	Peak FL
GR5, Low Load Humid Climate Grass	−57.6	−22.6	−21.3	38.9
GR6, Moderate Load, Humid Climate Grass	−47.4	−5.6	9.5	78.5
GR7, High Load, Dry Climate Grass	−25.0	29.3	54.0	146.5
GR8, High Load, Very Coarse, Humid Climate Grass	157.5	68.2	32.5	189.6

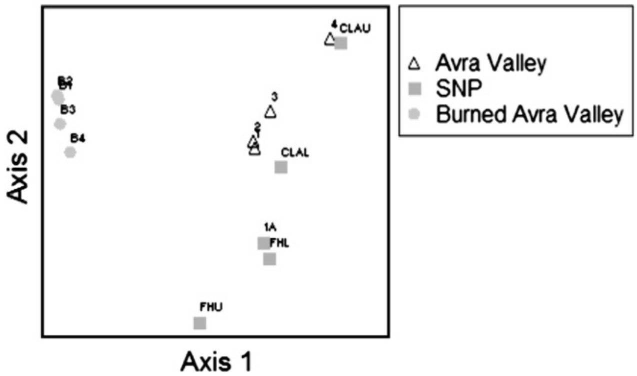

Fig. 6. Principal component analysis (PCA) ordination of native plant and buffelgrass cover in Avra Valley and SNP. The plots in Avra Valley are graphed twice: before treatment (triangles) and after treatment (circles) with prescribed fire. Axis 1 correlates with buffelgrass cover, bare ground and ash, while axis 2 negatively corresponds to cover of several native plants.

3.7. Fire behavior fuel modeling

In general, the fire behavior prediction program BEHAVE 4.0 (Andrews et al., 2008) does a decent job at predicting fire behavior in a buffelgrass-dominated community (Table 4). Fuel models that best predicted ROS generally overestimated peak FL. Closeness of fit varied with wind speed and fuel model. The moderate load, humid climate grass model (GR6) might be the best fit for landscape-level modeling of fire spread because it had the closest match at higher wind speeds when suppression accuracy is most critical. The models with lower fuel loads (low load, humid climate grass, GR5) and higher fuel loads (high load, dry climate grass, GR7 and high load, very coarse, humid climate grass, GR8) under- and overestimated ROS, respectively, at higher wind speeds.

4. Discussion

Fire in arid regions is viewed as a rare event (Schmid and Rogers, 1988), and historically, the lower elevations of the Sonoran Desert are no exception, as they experienced a near absence of fire activity (Wright and Bailey, 1982). Buffelgrass provides a case study to highlight the alteration of ecosystems and fire regimes that is occurring in arid lands across the globe (D'Antonio and Vitousek, 1992). The invasion of buffelgrass is transforming parts of the Lower Sonoran Desert into flammable grasslands, with intense fire behaviors, as measured in this study. This invaded plant community resembles a moderate load, humid climate grassland and not a desert. Buffelgrass is altering the fuel structure of the Sonoran Desert by creating continuous and abundant fuels, where none existed, increasing fire frequency (Brooks and Pyke, 2001) and fire behaviors observed in this study were much more severe than previously recorded in the Sonoran Desert. Buffelgrass is capable of invading even the hyperarid portions of the desert along the Gulf of California and is considered a serious potential threat to biodiversity there as well (West and Nabhan, 2002).

The discovery that fire behaviors from these buffelgrass-fueled fires fit most closely with a moderate load, humid climate grassland model, and not a more arid-climate fuel model, provides better insight to fire management and the potential effects of and change in community structure after a fire. The plant community and fuel model data in this study highlight that areas dominated by buffelgrass are not the typical Sonoran Desert, rather the vegetation, with or without fire, is more aptly described as a semi-tropical grassland. Extreme fire behaviors in this converted grassland community especially threatens shrubs and cacti and their absence is likely to increase community change (Stephan et al., 2010).

In this study post-fire plant community composition was significantly reduced. Over 80% of species encountered were absent after fire. Given that buffelgrass cover, native plant cover, fuel loads and weather patterns are similar at the undisturbed site, Saguaro National Park, it is expected that post-fire species richness would be similarly low. Also because of the similarities between sites a buffelgrass-fueled fire would be expected to burn with similarly intense fire behaviors. These buffelgrass-fueled fires generated enough heat to damage nearly 90% of photosynthetic tissue on cacti within the study area. Many long-lived succulent plants, including those in other arid landscapes, can suffer high mortality rates after even a single fire (McLaughlin and Bowers, 1982).

Conversion of native desert shrubland to buffelgrass grassland or savanna with frequent, intense fire will impact entire communities, including reptiles, birds, and arthropods (Bestelmeyer and Schooley, 1999; Brooks and Esque, 2002; Esque et al., 2003; Flanders et al., 2006). The most fire-sensitive plants include the dominant, signature species of the Sonoran Desert: columnar cacti such as saguaro and organ pipe (*Stenocereus thurberi* (Englm.) Buxbaum), and woody species such as littleleaf paloverde (*Parkinsonia microphylla* Torr.) and creosotebush (*Larrea tridentata* (D.C.) Coville) (Alford et al., 2005; Búrquez-Montijo et al., 2002; Cave and Patten, 1984; van Devender et al., 1997; Wilson et al., 1995). Not only does saguaro suffer high mortality from fire, but also its relationship with nurse plants complicates and exacerbates the impact of fire. Saguaro seedlings depend on nurse plants for survival (Turner et al., 1966), which when ignited can elevate saguaro mortality (McLaughlin and Bowers, 1982). The absence of nurse plants also retards saguaro recolonization of burned areas (Wilson et al., 1995). While some native plants can resprout after fire (Cave and Patten, 1984; Reynolds and Bohning, 1956; Rogers and Steele, 1980; White, 1969; Wright and Bailey, 1982), the ability of buffelgrass to resprout is much greater; many buffelgrass plants resprouted within five days after burning (CJM pers. obs.).

Historically, lower elevations of the Sonoran Desert act as natural fuel breaks. However, as buffelgrass abundances increase and fuel loads become continuous, fire will potentially move from the lower Sonoran Desert into montane habitats, and vice versa. Montane habitats in SNP and other areas of the Sonoran Desert experience fire intervals at less than ten years (Baisan and Swetnam, 1990; Wright and Bailey, 1982). Buffelgrass may provide a novel linkage between human-ignited fires in urban and suburban areas and lightning-ignited fires in high elevations, threatening human and natural communities with increased fire frequencies while also contributing to increased fires in montane systems during seasons when fire is historically rare or absent.

Observed fire behaviors were more intense than compared to other arid ecosystems in the southwestern United States. In the Mojave Desert fires fueled by the annual red brome (*Bromus madritensis* L. ssp. *rubens* (L.) Husn.), have rates of spread 3–7 times lower (Brooks, 1999) and flame lengths were 13–24 times lower (Brooks, 2002) than observed in this study. Compared to fires in mesquite-acacia shrublands in Texas, the rate of spread observed here was 4–12 times faster (Streeks et al., 2005). In the current study fuel moisture values were low, yet they mirrored values in other studies (Bragg, 1982; Esque et al., 2007; Streeks et al., 2005). Observed fire behaviors will resemble wildfire behaviors from April to July, *ceteris paribus*, when buffelgrass fuel moisture is low in late spring but before the summer 'monsoon' rains begin. Because buffelgrass can burn during the growing season (Martin-R et al., 1999) it may extend the historical fire season during a time when many native plants are actively growing (July–September).

Significantly, buffelgrass is causing a decrease in the cover and richness of native plants, without the influence of fire. Buffelgrass is a fast-growing and water-use-efficient C_4 plant, and more than capable of invading the C_3- and CAM-dominated native flora (De la Barrera and Castellanos, 2007; Ward et al., 2006). This study suggests buffelgrass does not preferentially invade species-poor communities, but rather invades favorable microsites and then decreases native plant cover and richness in and around those microsites. This pattern of invasive species being the cause of decreased richness is documented across many sites (Myers et al., 2000), with other non-native plants in the Sonoran Desert (Búrquez-Montijo et al., 2002; Mau-Crimmins, 2005) and has been documented in buffelgrass populations locally and around the world (Burgess et al., 1991; Daehler and Goergen, 2005; De la Barrera, 2008; Franks, 2002; Jackson, 2005; West and Nabhan, 2002).

Because deserts generally have an abundance of hazardous fire weather i.e. hot, dry and windy days, and because invasive plants are increasing fuel loads where fuels were once scarce, fires fueled by invasive plants can produce extreme fire behaviors. Buffelgrass burned in this study with enough intensity that even low to moderate fuel loads could have significant negative effects on native vegetation. Over the range of conditions examined here, and considering the variability and sample sizes, fuel load was less important in predicting fire behavior than weather (see Byram, 1959 and Wright and Bailey, 1982). The hot, dry and windy weather in arid lands can strengthen what would in a more mesic locale produce less intense, and less adverse, fire behavior, given similar fuel loads. If previous studies are representative, then average fuel loads in this study were extremely high–more than 10–40 times the minimum amount of fine fuel necessary to carry a fire in semi-arid ecosystems (20 g/m^2 Brooks, 1999; 67 g/m^2 Wright, 1980). In order to return to a historic fire regime common among arid lands, where fires rarely occur, and because weather patterns in arid lands can exacerbate intense fire behaviors, buffelgrass fuel loads will need to be reduced by 92–98%. However in the long-term, complete eradication is a more effective management goal.

4.1. Management Implications

Fires fueled by non-native annual plants are easily suppressed by hand tools and back-pack pumps (Brooks, 2002), but buffelgrass-fueled fires require engines, bulldozers, or burning out from some distance from the fire to ensure containment. Fire behavior influences the tactics that can be used in fighting fires, the size of firefighter safety zones, and how many safety zones will be available near the fire. Flame lengths (FL) and rates of spread observed in this study were great enough that fire fighters could not fight buffelgrass fires directly with hand tools, but used equipment and fought the fires indirectly, e.g., by burning out from fuel breaks. Fuel breaks in grassy fuels are traditionally desired to be about 1.5 times greater than FL (Byram, 1959) thus viable fuel breaks should be greater than 5 m wide.

Practitioners in arid lands may focus their attention and resources on the densest patches of invasive grass, yet they may miss the opportunity to remove less-dense patches, which would still be very flammable and which serve as nascent foci for subsequent spread (Moody and Mack, 1988). In addition less-dense patches can have the highest rates of growth. For example, over a 2-year period a single buffelgrass patch increased from 3 to 73 plants (USDI, 2009). Removal of the vast majority of fuel is necessary to return to the historic fire regime found in many arid lands: infrequent to rare occurrences. This will need to be conducted by removing both dense patches and less-dense patches. Removal of invasive plants in the early stages of infestation enhances native plant preservation, decreases restoration costs and less-dense patches can provide managers with the necessary experience before tackling dense patches (Bainbridge, 2007). Critical thought should be given to removing less-dense patches first and management decisions should be based on site-specific ecological and economic factors.

Results of some small fires in buffelgrass patches have been noted (M. Brooks cited in Rice et al., 2008; Rutman and Dickson, 2002; CJM pers. obs.), and if patterns of buffelgrass encroachment persist, large fires are predicted to occur in the near future. Decades to centuries could pass before post-fire species composition resembles that which existed before a fire in the Sonoran Desert (Abella, 2009). Even if fires are suppressed, reintroduction of native plants into highly degraded areas could be problematic for a multitude of reasons (Whisenant, 1999). Williams and Baruch (2000), summarize the effects of buffelgrass on native plants well: "buffelgrass constitutes a singular threat to the biological diversity of the Sonoran Desert" (pp. 127–128).

Acknowledgements

Funding for this project was provided by the National Park Service. City of Tucson Water Department provided land for the experimental burning and logistical support. National Park Service, Avra Valley Fire District, Buenos Aires National Wildlife Refuge, Coronado National Forest, Northwest Fire, and Tubac Fire Department provided assistance during the burn.

References

Abella, S.R., 2009. Post-fire plant recovery in the Mojave and Sonoran deserts of western north America. Journal of Arid Environments 73, 699–707.
Alford, E.J., Brock, J.H., Gottfried, G.J., 2005. Effects of fire on Sonoran Desert plant communities, in Gottfried, G.J., Gebow, B.S., Eskew, L.G., Edminster, C.B. (comps.), Connecting Mountain Islands and Desert Seas: Biodiversity and Management of the Madrean Archipelago II, May 11–15, Tucson, AZ. Proceedings RMRS-P-36, Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp. 451–455.
Anderson, H.E., 1982. Aids to determining fuel models for estimating fire behavior, Gen. Tech. Rep. INT- 122. Department of Agriculture, Forest Service, Intermountain forest and range Experiment Station, Ogden, UT, pp. 22.
Andrews, P.L., Bevins, C.D., Seli, R.C., 2008. BehavePlus fire modeling system, version 4.0: User's Guide. General Technical Report RMRS-GTR-106WWW Revised. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 116.
Arriaga, L., Castellanos, A.E., Moreno, V.E., Alarcón, J., 2004. Potential ecological distribution of alien invasive species and risk assessment: a case study of buffel grass in arid regions of Mexico. Conservation Biology 18, 1504–1514.
Bainbridge, D.A., 2007. A Guide for Desert and Dryland Restoration: New Hope for Arid Lands. Island Press, Washington DC.
Baisan, C.H., Swetnam, T.W., 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, USA. Canadian Journal of Forest Research 20, 1559–1569.
Bestelmeyer, B.T., Schooley, R.L., 1999. The ants of the southern Sonoran desert: community structure and the role of trees. Biodiversity and Conservation 8, 643–657.
Bragg, T.B., 1982. Seasonal variation in fuel and fuel consumption by fires in a bluestem prairie. Ecology 63, 7–11.
Brooks, M.L., 1999. Alien annual grasses and fire in the Mojave Desert. Madroño 46, 13–19.
Brooks, M.L., 2002. Peak fire temperatures and effects on annual plants in the Mojave Desert. Ecological Applications 12, 1088–1102.
Brooks, M.L., Esque, T.C., 2002. Alien plants and fire in desert tortoise (*Gopherus agassizii*) habitat of the Mojave and Colorado Deserts. Chelonian Conservation and Biology 4, 330–340.
Brooks, M.L., Pyke, D.A., 2001. Invasive plants and fire in the deserts of North America, in Galley, K.E.M., Wilson, T.P. (eds.). Proceedings of the Invasive Species Workshop: The Role of Fire in the Control and Spread of Invasive Species, Fire Conference 2000: The First National Congress on Fire Ecology, Prevention, and Management. Miscellaneous Publication No. 11, Tall Timbers Research Station, Tallahassee, FL, pp. 1–14.
Brown, D.E., 1994. Biotic Communities: South-western United States and North-western Mexico. University of Utah Press, Salt Lake City.
Bunting, S.C., Wright, H.A., Neuenschwander, L.F., 1980. Long-term effects of fire on cactus in the southern mixed prairie of Texas. Journal of Range Management 33, 85–88.
Burgess, T.L., Bowers, J.E., Turner, R.M., 1991. Exotic plants at the desert laboratory, Tucson, Arizona. Madroño 38, 96–114.

Búrquez-Montijo, A., Miller, M.E., Martínez-Yrízar, A., 2002. Mexican grasslands, thornscrub, and transformation of the Sonoran Desert by invasive exotic buffelgrass (*Pennisetum ciliare*). In: Tellman, B. (Ed.), Invasive Exotic Species in the Sonoran Region. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, AZ, pp. 126–146.

Butler, D.W., Fairfax, R.J., 2003. Buffel grass and fire in a Gidgee and Brigalow woodland: a case study from central Queensland. Ecological Management and Restoration 4, 120–125.

Byram, G.M., 1959. Combustion of forest fuels. In: Davis, K.P. (Ed.), Forest Fire Control and Use. McGraw-Hill Book Company, New York, pp. 61–89.

Cable, D.R., 1965. Damage to mesquite, Lehmann lovegrass and black grama by a hot June fire. Journal of Range Management 18, 326–329.

Cable, D.R., 1967. Fire effects on semidesert grasses and shrubs. Journal of Range Management 20, 170–176.

Cave, G.H., Patten, D.T., 1984. Short-term vegetation responses to fire in the Upper Sonoran Desert. Journal of Range Management 37, 491–496.

Cheney, N.P., Gould, J.S., 1995. Fire growth in grassland fuels. International Journal of Wildland Fire 5, 237–247.

Clarke, P.J., Latz, P.K., Albrecht, D.E., 2005. Long-term changes in semi-arid vegetation: invasion of an exotic perennial grass has larger effects than rainfall variability. Journal of Vegetation Science 16, 237–248.

Cohn, J.P., 2005. Tiff over tamarisk: can a nuisance be nice, too? BioScience 55, 648–654.

Daehler, C.C., Goergen, E.M., 2005. Experimental restoration of an indigenous Hawaiian grassland after invasion by buffel grass (*Cenchrus ciliaris*). Restoration Ecology 13, 380–389.

D'Antonio, C.M., Vitousek, P.M., 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23, 63–87.

De la Barrera, E., 2008. Recent invasion of buffel grass (*Cenchrus ciliaris*) of a natural protected area from the southern Sonoran Desert. Revista Mexicana de Biodiversidad 79, 385–392.

De la Barrera, E., Castellanos, A.E., 2007. High temperature effects on gas exchange for the invasive buffel grass (*Pennisetum ciliare* [L.] Link). Weed Biology and Management 7, 128–131.

Esque, T.C., Schwalbe, C.R., 2002. Mexican grasslands, thornscrub, and transformation of the Sonoran Desert by invasive exotic buffelgrass (*Pennisetum ciliare*). In: Tellman, B. (Ed.), Invasive Exotic Species in the Sonoran Region. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, AZ, pp. 165–194.

Esque, T.C., Schwalbe, C.R., DeFalco, L.A., Duncan, R.B., Hughes, T.J., 2003. Effects of desert wildfires on desert tortoise (*Gopherus agassizii*) and other small vertebrates. Southwestern Naturalist 48, 103–111.

Esque, T.C., Schwalbe, C.R., Haines, D.F., Halvorson, W.L., 2004. Saguaros under siege: invasive species and fire. Desert Plants 20, 49–55.

Esque, T.C., Schwalbe, C.R., Lissow, J.A., Haines, D.F., Foster, D., Garnett, M.C., 2007. Buffelgrass fuel loads in Saguaro National Park, Arizona, increase fire danger and threaten native species. Park Science 24, 33–56.

Flanders, A.A., Kuvlesky Jr., W.P., Ruthven III, D.C., Zaiglin, R.E., Bingham, R.L., Fulbright, T.E., Hernández, F., Brennan, L.A., 2006. Effects of invasive exotic grasses on South Texas rangeland breeding birds. The Auk 123, 171–182.

Franks, A.J., 2002. The ecological consequences of Buffel Grass *Cenchrus ciliaris* establishment within remnant vegetation of Queensland. Pacific Conservation Biology 8, 99–107.

Gibson, A.C., 1996. Structure-function of Warm Desert Plants. Springer Verlag, Berlin.

Humphrey, R.R., 1974. Fire in the deserts and desert grassland of North America. In: Kozlowski, T.T., Ahlgren, C.E. (Eds.), Fire and Ecosystems. Academic Press, New York, pp. 366–400.

Jackson, J., 2005. Is there a relationship between herbaceous species richness and buffel grass (*Cenchrus ciliaris*)? Austral Ecology 30, 505–517.

Low, T., 1997. Tropical pasture plants as weeds. Tropical Grasslands 31, 337–343.

Martin-R, M., Cox, J.R., Ibarra-F, F., Alston, D.G., Banner, R.E., Malecheck, J.C., 1999. Spittlebug and buffelgrass responses to summer fires in Mexico. Journal of Range Management 52, 621–625.

Mau-Crimmins, T.M., 2005. The prospects for spread and removal of Eragrostis lehmanniana Nees. Ph.D. Dissertation, University of Arizona, Tucson.

McLaughlin, S.P., Bowers, J.E., 1982. Effects of wildfire on a Sonoran Desert plant community. Ecology 63, 246–248.

McPherson, G.R., 1995. The role of fire in the desert grasslands. In: McClaran, M.P., Van Devender, T.R. (Eds.), The Desert Grassland. University of Arizona Press, Tucson, pp. 130–151.

Moody, M.E., Mack, R.N., 1988. Controlling the spread of plant invasions: the importance of nascent foci. Journal of Applied Ecology 25, 1009–1021.

Myers, J.H., Simberloff, D., Kuris, A.M., Carey, J.R., 2000. Eradication revisited: dealing with exotic species. Trends in Ecology and Evolution 15, 316–320.

Reynolds, H.G., Bohning, J.W., 1956. Effects of burning on a desert grass-shrub range in southern Arizona. Ecology 37, 769–777.

Rice, P.M., McPherson, G.R., Rew, L.J., 2008. Fire and nonnative invasive plants in the Interior West Bioregion. In: Zouhar, K., Smith, J.K., Sutherland, S., Brooks, M.L. (Eds.), Wildland Fire in Ecosystems: Fire and Nonnative Invasive Plants. Gen. Tech. Rep. RMRS-GTR-42, vol. 6. USDA, Forest Service, Rocky Mountain Research Station, Ogden, UT, pp. 141–173.

Rogers, G.F., 1985. Mortality of burned *Cereus giganteus*. Ecology 66, 630–632.

Rogers, G.F., 1986. Comparison of fire occurrence in desert and nondesert vegetation in Tonto National Forest, Arizona. Madroño 33, 278–283.

Rogers, G.F., Steele, J., 1980. Sonoran Desert fire ecology. In: Stokes, M.A., Dieterich, J.H. (Eds.), Proceedings of the Fire History Workshop. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 15–19. General Technical Report RM-GTR-81.

Rutman, S., Dickson, L., 2002. Management of buffelgrass on organ pipe cactus National Monument, Arizona. In: Tellman, B. (Ed.), Invasive Exotic Species in the Sonoran Region. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, AZ, pp. 311–318.

Schmid, M.K., Rogers, G.F., 1988. Trends in fire occurrence in the Arizona upland subdivision of the Sonoran Desert, 1955 to 1983. The Southwestern Naturalist 33, 437–444.

Schroeder, M.J., Buck, C.C., 1970. Fire Weather: A Guide for Application of Meteorological Information to Forest Fire Control Operations. USDA Forest Service. Agriculture Handbook 360.

Scott, J.H., Burgan, R.E., 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. Gen. Tech. Rep. RMRS-GTR-153. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Simmons, D., Adams, R., Stoner, J., 2006. Fuels of the future: the challenge of new fuel types. Paper number 15 in Life in a Fire-Prone Environment: Translating Science into Practice. Bushfire Conference 2006, Brisbane, 6–9 June 2006.

Stephan, K., Miller, M., Dickenson, M.B., 2010. First order fire effects on herbs and shrubs: present knowledge and process modeling needs. Fire Ecology 6, 96–114.

Streeks, T.J., Owens, M.K., Whisenant, S.G., 2005. Examining fire behavior in mesquite-acacia shrublands. International Journal of Wildland Fire 14, 131–140.

Thomas, P.A., 2006. Mortality over 16 years of cacti in a burnt desert grassland. Plant Ecology 183, 9–17.

Tjelmeland, A.D., Fulbright, T.E., Lloyd-Reilley, J., 2008. Evaluation of herbicides for restoring native grasses in buffelgrass-dominated grasslands. Restoration Ecology 16, 263–269.

Turner, R.M., Alcorn, S.M., Olin, G., Booth, J.A., 1966. The influence of shade, soil, and water on saguaro seedling establishment. Botanical Gazette 127, 95–102.

USDI, 2003. Fire Monitoring Handbook. United States Department of the Interior, National Park Service, Fire Management Program Center, National Interagency Fire Center, Boise, ID. 274 p.

USDI, 2007. Saguaro National Park Fire Management Plan. United States Department of the Interior, National Park Service, Tucson, AZ. 157 p.

USDI, 2009. Buffelgrass and Fountaingrass Management Program: Field Season Report, Fall 2008-Spring 2009 Organ Pipe Cactus National Monument. National Park Service, Ajo, AZ. 9 p.

van Devender, T.R., Felger, R.S., Búrquez, M.A., 1997. Exotic Plants in the Sonoran Desert Region, Arizona and Sonora. In: Kelly, M., Wagner, E., Warner, P. (Eds.), Proceedings of the California Exotic Pest Plant Council Symposium, 3. California Exotic Pest Plant Council, Berkeley, CA, pp. 1–6.

Ward, J.P., Smith, S.E., McClaran, M.P., 2006. Water requirements for emergence of buffelgrass (*Pennisetum ciliare*). Weed Science 54, 720–725.

West, P., Nabhan, G.P., 2002. Invasive plants: their occurrence and possible impact on the central Gulf Coast of Sonora and the Midriff Islands in the Sea of Cortés. In: Tellman, B. (Ed.), Invasive Exotic Species in the Sonoran Region. University of Arizona Press and The Arizona-Sonora Desert Museum, Tucson, AZ, pp. 90–111.

Whisenant, S.G., 1999. Repairing Damaged Wildlands: a Process-Oriented, Landscape-Scale Approach. Cambridge University Press, Cambridge, United Kingdom.

White, L.D., 1969. Effects of a wildfire on several desert grassland shrub species. Journal of Range Management 22, 284–285.

Williams, D.G., Baruch, Z., 2000. African grass invasion in the Americas: ecosystem consequences and the role of ecophysiology. Biological Invasions 2, 123–140.

Wilson, R.C., Narog, M.G., Koonce, A.L., Corcoran, B.M., 1995. Postfire regeneration in Arizona's giant saguaro shrub community. In: DeBano, L.F., Gottfried, G.J., Hamre, R.H., Edminster, C.B., Ffolliott, P.F., Ortega-Rubio, A. (Eds.), Proceedings of Biodiversity and Management of the Madrean Archipelago. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, pp. 424–431. General Technical Report RM-GTR-264.

Wright, H.A., 1980. The Role and Use of Fire in the Semidesert Grass-shrub Type. Forest Service General Technical Report INT 85, Intermountain Forest and Range Experiment Station, Ogden, UT.

Wright, H.A., Bailey, A.W., 1982. Fire Ecology, United States and Southern Canada. Wiley, New York.

Zouhar, K., Smith, J.K., Sutherland, S., 2008. Effects of fire on nonnative invasive plants and invasibility of wildland ecosystems. In: Zouhar, K., Smith, J.K., Sutherland, S., Brooks, M.L. (Eds.), Wildland Fire in Ecosystems: Fire and Nonnative Invasive Plants. Gen. Tech. Rep. RMRS-GTR-42, vol. 6. USDA, Forest Service, Rocky Mt. Res. Sta., Ogden, UT, pp. 7–31.