CSIRO PUBLISHING

International Journal of Wildland Fire **2013**, *22*, 353–358
http://dx.doi.org/10.1071/WF11161

Research Note

Exotic annual grass invasion alters fuel amounts, continuity and moisture content

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Abstract. Many exotic annual grasses are believed to increase wildfire frequency to the detriment of native vegetation by increasing fine fuels and thus, creating a grass-fire cycle. However, information on differences in fuel characteristics between invaded and non-invaded plant communities is lacking, or is based mainly on speculation and anecdotal evidence. We compared fuel biomass, cover, continuity and moisture content in plant communities invaded and not invaded by cheatgrass (*Bromus tectorum* L.), an exotic annual grass, in 2010 and 2011 in south-eastern Oregon, USA. Annual grass-invaded communities had higher fine fuel amounts, greater fuel continuity, smaller fuel gaps and lower fuel moisture content than did non-invaded plant communities. These conditions would increase the probability that ignition sources would contact combustible fuels and that fires would propagate. Fuel characteristics in the annual grass-invaded communities in our study may also support faster spreading fires. Fuel moisture content was low enough to burn readily more than a month earlier in annual grass-invaded communities than in non-invaded communities, thereby expanding the wildfire season. The cumulative effect of these differences in fuel characteristics between exotic annual grass-invaded and non-invaded plant communities is an increased potential for frequent, large-scale, fast-spreading wildfires. We suggest that research is needed to develop methods to mediate and reverse these changes in fuel characteristics associated with *B. tectorum* invasion.

Additional keywords: cheatgrass, fire risk, invasive plants, wildfire.

Received 11 November 2011, accepted 14 June 2012, published online 3 October 2012

Introduction

Alterations to fire regimes by exotic plant invasion are common around the world and are especially devastating when they result in fires that occur too frequently for most native vegetation to tolerate (D'Antonio and Vitousek 1992; Mack *et al.* 2000; Brooks *et al.* 2004). Exotic grasses commonly increase fire frequency and create a positive feedback cycle (grass–fire cycle) between fire and their continued dominance of plant communities (D'Antonio and Vitousek 1992; Rossiter *et al.* 2003). The grass–fire cycle occurs when exotic grasses increase the amount and continuity of fine fuel, which increases fire frequency (Rossiter *et al.* 2003). The grass–fire cycle has helped exotic grasses invade substantial areas on almost every continent (D'Antonio and Vitousek 1992; Rossiter *et al.* 2003; Milton 2004).

Although exotic perennial grasses are a serious problem throughout the world, exotic annual grasses are especially challenging in arid and semiarid regions of western North America, Africa, Asia and Australia (Purdie and Slatyer 1976; Mack 1981; Hobbs and Atkins 1988, 1990; Brooks *et al.* 2004; Milton 2004; Liu *et al.* 2006; Davies and Svejcar 2008; Davies 2011). These invasions are often an ecosystem-level change that converts savannas, shrublands and shrub-grasslands to near monocultures of annual grasses by greatly increasing wildfire frequency (Whisenant 1990; D'Antonio and Vitousek 1992; Brooks *et al.* 2004; Davies 2011). Dominance by exotic annual grasses is speculated to increase wildfire frequency because it increases the amount (Stewart and Hull 1949; Whisenant 1990; D'Antonio and Vitousek 1992; Knapp 1995), horizontal continuity and ignitability of fuels (Brooks 2008). Increased continuity of fine fuels elevates the risk of wildfires and facilitates their spread once ignited (Waldram *et al.* 2008; Davies *et al.* 2010). Variation in fire frequency in rangelands is driven by fine fuel continuity in addition to abundance (Miller and Heyerdahl 2008). However, information on fine fuel amounts and continuity in exotic annual grass-invaded communities relative to that in non-invaded communities is poorly documented.

Modifications to fine fuel moisture by exotic annual grasses may also influence the risk and behaviour of wildfires. Fuel moisture plays a critical role in the susceptibility of plant communities to burning (Flannigan and Wotton 1991; Thonicke *et al.* 2001; Chuvieco *et al.* 2004; Manzello *et al.* 2006). Fuel moisture content also affects the rate of fire spread. As moisture content of fuels increases, more energy is required to heat fuels to combustion, translating into slower rates of spread

(Thonicke *et al.* 2001). Therefore, the effects of exotic annual grass invasion on fine fuel moisture as well as fuel amount and continuity are important factors determining the potential risk and severity of wildfires. To date, information on the influence of exotic annual grasses on fuel characteristics is based mainly on speculation and anecdotal evidence. Without a thorough understanding of the effects of exotic annual grasses on fuel characteristics, it is difficult to justify, prioritise and plan actions to manage fuels to reduce the risk of wildfires.

The objective of this study was to determine the effect of exotic annual grass invasion on fine fuel characteristics. To accomplish this objective, we evaluated the effect of cheatgrass (*Bromus tectorum* L.) invasion on fine fuel characteristics. This species is the most widespread and ecologically significant exotic annual grass in North America. It is believed to have reduced fire return intervals from 50 to +100 years to 3–5 years in sagebrush plant communities in the western United States (Stewart and Hull 1949; Whisenant 1990). *Bromus tectorum*-invaded rangelands appear to burn more readily than non-invaded rangelands (Stewart and Hull 1949; Whisenant 1990). Although *B. tectorum* invasion has been repeatedly reported to have altered fuel characteristics in plant communities, and to promote frequent, large-scale fires (Young and Evans 1978; Whisenant 1990; Knapp 1996; Brooks *et al.* 2004; Keane *et al.* 2008; Pierson *et al.* 2011), quantification of changes in fuel characteristics with invasion are lacking. Thus, despite the many efforts documented above and elsewhere, and the importance of the *B. tectorum*-sagebrush example to the field of exotic species transforming fire regimes, the basics of its fuel dynamics have yet to be quantified. We hypothesised that *B. tectorum* invasion alters fuel characteristics that increase the risk of frequent wildfires with little unburned area inside the fire perimeter. Specifically, we expected: (1) higher fine fuel loads, (2) lower fuel moisture and (3) greater continuity of fuels in exotic annual grass-invaded compared with non-invaded plant communities. To test our hypotheses, we compared fuel characteristics between exotic annual grass-invaded and non-invaded plant communities at four sites in 2010 and 2011.

Methods

Study area

The study was conducted at the Northern Great Basin Experimental Range (NGBER) in south-eastern Oregon (43°29′N, 119°43′W) ~56 km west of Burns, OR, USA. The climate is typical of the northern Great Basin with cool, wet winters and hot, dry summers. Mean annual temperature is 8°C with winter and summer recorded extremes of −29 and 42°C. The NGBER received on average 284 mm of precipitation annually during the past 50 years (1956–2005). Crop-year (1 October–30 September) precipitation was 101 and 118% of this long-term average in 2010 and 2011 (Eastern Oregon Agricultural Research Center weather data). Study sites were located on west- or south-facing slopes (3–7°) at elevations of ~1400 to 1500 m above sea level. Soils at the study sites are Aridisols and Andisols with shallow to moderately deep profiles before reaching a restrictive layer. Prior to the study, livestock grazing was moderate (~40% use of available forage) for the past +50 years with occasional years of complete rest. Grazing pressure ranged between 0.15 and 0.36 animal unit months (AUMs) per hectare with an average of 0.22 AUMs per hectare. Potential natural plant communities would have been *Artemisia tridentata* ssp. *wyomingensis* (Beetle & A.Young) S.L.Welsh shrub overstoreys with perennial bunchgrass understoreys at all sites. Annual grass-invaded plant communities were near monocultures of *B. tectorum* with some exotic annual forbs. *Achnatherum thurberianum* (Piper) Barkworth), *Festuca idahoensis* Elmer, *Koeleria macrantha* (Ledeb.) J.A.Schultes, *Pseudoroegneria spicata* (Pursh) A.Löve and *Elymus elymoides* (Raf.) Swezey were common bunchgrasses in the non-invaded plant communities.

Experimental design

To determine the effects of *B. tectorum* invasion on fuel characteristics a block design with four blocks was used. Each of the four blocks contained adjacent annual grass-invaded and non-invaded communities separated by roads that acted as fire breaks during previous fires. Previously burned areas within each block were heavily invaded by *B. tectorum*, whereas the unburned areas were dominated by native vegetation. Sites were located 50 m from the road to reduce the road effect; however, the effect was probably minimal. Roads experienced little traffic as they were unmaintained and their primary purpose was to allow staff to monitor rangeland conditions across the NGBER. Fires occurred 4 to 6 years before the study. Treatments were exotic annual grass-invaded and non-invaded plant communities. The annual grass-invaded and non-invaded communities in each block had similar soils and topography and occurred in the same grazing allotment. Grazing by livestock was excluded during the study.

Measurements

Fine (herbaceous) fuel characteristics were measured in 2010 and 2011. Fuel moisture content was measured from June through August and fuel biomass and continuity were measured in August of each year. Measurements were collected during this time period to coincide with the wildfire (dry) season. The peak of the wildfire season is usually late July through early- to mid-August in this area (Davies *et al.* 2010). Fuel moisture was determined approximately every 2 weeks by harvesting all herbaceous vegetation in five 0.20-m^2 frames, weighing the harvested biomass, oven drying it to a constant weight and weighing the dried biomass in each treatment in every block. Fuel moisture was then calculated as a percent of dry weight. Fuel biomass was determined by harvesting 15 randomly located 1-m^2 frames in each treatment replicate. Harvested biomass was oven-dried to a constant weight and then weighed to determine fuel biomass. Two 20-m transects, spaced at 15-m intervals were used to measure fine fuel, gap and shrub cover using the line-intercept method (Canfield 1941) in each treatment replicate. Gaps were areas lacking fuels (e.g. bare ground, rocks and crusts). Total cover was determined by combining shrub and fine fuel cover. To determine fuel continuity, the length of individual patches of fine fuel, gap and shrub cover were measured on the two 20-m transects. Patches of the same cover type separated by <5 cm on the line intercept transect were considered the same patch and patches separated by ≥5 cm were considered individual patches. Density of individual fine fuel, gap and shrub patches were counted on the two 20-m transects. If the transect bisected an individual patch it was counted. Density was then calculated by metre of transect by dividing the number of recorded patches per transect by transect length.

Statistical analysis

Repeated analysis of variance was used to compare fuel characteristics between annual grass-invaded and non-invaded plant communities using the PROC MIXED method in SAS *v*.9.1 (SAS Institute Inc., Cary, NC). Treatment was included as a fixed variable and site and site by treatment interactions were treated as random variables in the analyses. Covariance structures were determined using the Akaike's Information Criterion (Littell *et al.* 1996). Treatment effects were also analysed in each sampling period. Data were tested for normality with the univariate procedure in SAS *v*.9.1 (Littell *et al.* 1996). Data that did not meet assumptions of normality were log-transformed. All figures display original, non-transformed data.

Results

Invaded and non-invaded plant communities differed in all measured major response variables. Fine fuel biomass varied by treatment ($P = 0.005$), but the interaction between treatment and year was not significant ($P = 0.162$). Fine fuel biomass was 3- and 2-fold greater in the annual grass-invaded compared with the non-invaded plant community in 2010 and 2011. Fine fuel biomass was 1109 ± 30 and 349 ± 24 kg ha^{-1} in the annual grass-invaded and non-invaded plant communities in 2010. In 2011, fine fuel biomass was 1060 ± 139 and 562 ± 59 kg ha^{-1} in the annual grass-invaded and non-invaded communities. Fine fuel water content varied by the interaction between treatment and sampling date ($P = 0.008$). On most sampling dates fuel water content was greater in the non-invaded than the annual grass-invaded communities (Fig. 1; $P < 0.05$); however, we did not find evidence that fuel water content differed between treatments on the earliest sampling date in 2011 ($P = 0.336$). In mid-July, fuel water content was between 6.8- and 26.7-fold greater in non-invaded than in annual grass-invaded communities. Fine fuel, shrub, total and gap cover were not influenced by the interaction between treatment and year ($P > 0.05$), but varied by treatment (Fig. 2; $P < 0.005$). In 2010 and 2011, fine fuel cover was 2.4- and 2.2-fold higher in the annual grass-invaded than in the non-invaded community. Shrub cover averaged zero and 20% in the annual grass-invaded and non-invaded communities. Total cover was ~1.5-fold higher in the annual grass-invaded than in non-invaded communities. Gap cover was 7- and 10-fold greater in non-invaded than in annual grass-invaded plant communities in 2010 and 2011. Average length of continuous fine fuel cover varied by the interaction between treatment and year ($P = 0.038$). In 2010 and 2011, fine fuel cover length was 9- and 17-fold greater in the annual grass-invaded than in non-invaded communities (Fig. 3; $P = 0.010$ and <0.001). The length of continuous shrub and gap cover did not vary by the interaction between treatment and year ($P = 0.279$ and 0.979), but varied by treatment ($P = 0.025$ and 0.034). Shrub length averaged 0 and 46 cm in the annual grass-invaded and non-invaded communities. Length of gap cover was ~2-fold higher in the non-invaded than in the annual grass-invaded communities in 2010 and 2011. The fine fuel, gap and shrub patch densities varied by treatment (Fig. 3; $P < 0.001$), but were not influenced by the interaction between treatment and

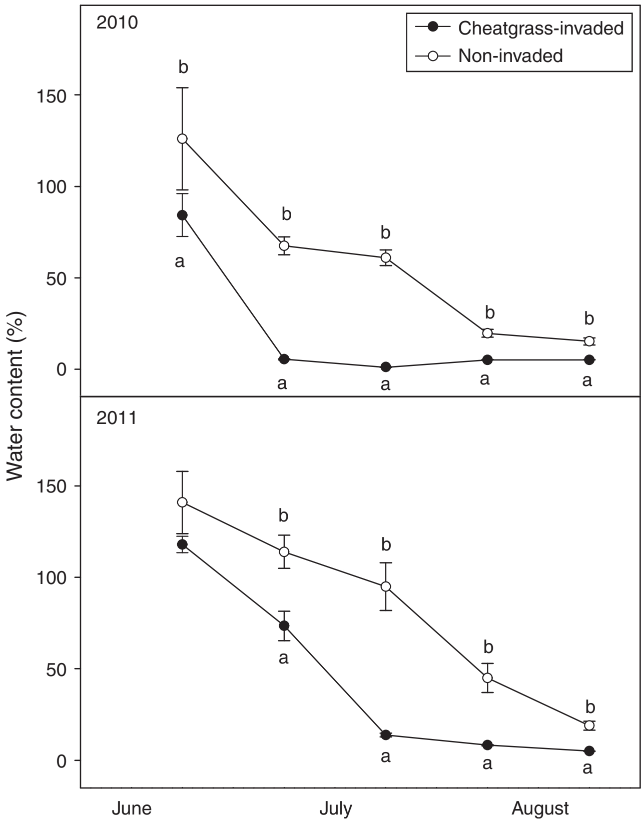

Fig. 1. Fine fuel water content (mean ± s.e.) in annual grass-invaded and non-invaded plant communities in south-eastern Oregon in 2010 and 2011. Water content calculated as a percent of dry weight. Different lower case letters indicate a significant difference ($P < 0.05$) between treatments on that date.

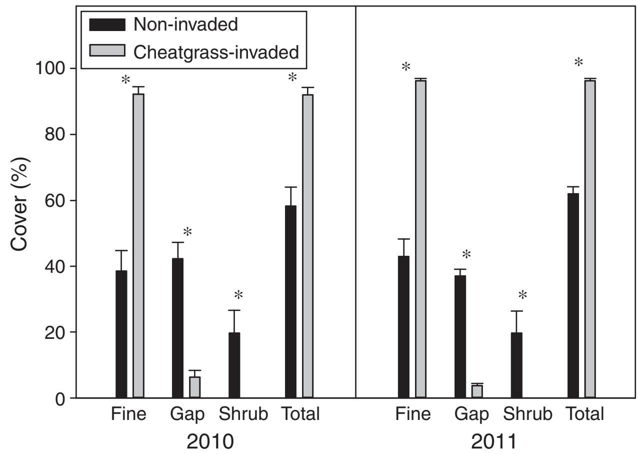

Fig. 2. Cover (mean ± s.e.) in annual grass-invaded and non-invaded plant communities in south-eastern Oregon in 2010 and 2011. Fine, fine fuels; Gap, fuel gaps; Total, fine fuels and shrub cover combined. Asterisks (*) indicate significant ($P < 0.05$) within-year difference between treatments.

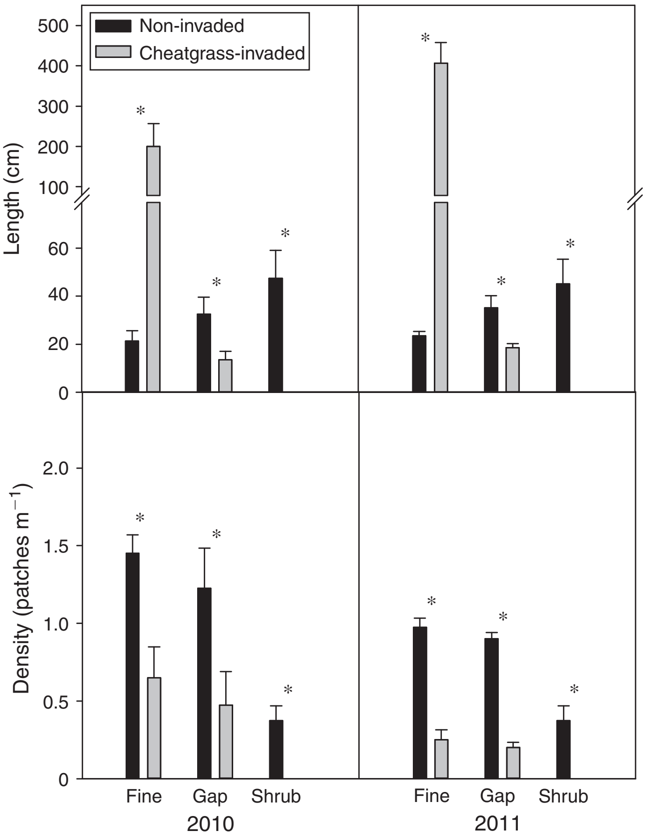

Fig. 3. Patch density and length (mean ± s.e.) in annual grass-invaded and non-invaded plant communities in south-eastern Oregon in 2010 and 2011. Fine, fine fuels; Gap, fuel gaps. Asterisks (*) indicate significant ($P < 0.05$) within-year difference between treatments.

year ($P > 0.05$). Density of fine fuel patches was 2.3- to 3.9-fold greater in the non-invaded than in the annual grass-invaded communities. Gap density was 2.6- and 4.5-fold higher in the non-invaded than in the annual grass-invaded communities in 2010 and 2011. Shrub density averaged 0.0 and 0.4 patches m^{-1} in annual grass-invaded and non-invaded communities.

Discussion

Plant communities invaded by exotic annual grass in our study have vastly different fuel characteristics from non-invaded communities. This study provides data to support previous assumptions (Brooks 2008; Keane *et al.* 2008; Rice *et al.* 2008) that *B. tectorum*-invaded plant communities have greater fine fuel loads, lower fuel moisture content and greater fuel continuity than do non-invaded plant communities. These results also support previous accounts that modification of plant community fine fuel characteristics with *B. tectorum* invasion increases the risk of fires (Whisenant 1990; Knapp 1996; Brooks *et al.* 2004; Keane *et al.* 2008; Pierson *et al.* 2011). The probability for fire ignition and subsequent propagation is likely to be increased in *B. tectorum*-invaded communities due, in part, to elevated fine fuel amounts and continuity. Ignition sources would be much more likely to make contact with combustible fuels in *B. tectorum*-invaded communities, because fuels cover more than 90% of the ground in the *B. tectorum*-invaded communities, compared with ~60% in the non-invaded communities. In addition, increases in fine fuel amounts increase flame length, and fires spread faster as flame lengths and fuel continuity increase, assuming other factors influencing fire spread are held constant (Bradstock and Gill 1993; Blackmore and Vitousek 2000).

Decreased fuel moisture with *B. tectorum* invasion has important implications for fire risk and seasonality. Lower fuel moisture content in *B. tectorum*-invaded plant communities can increase the likelihood that an ignition source would contact fuels dry enough to ignite, compared with that in non-invaded communities. Specifically, lower fuel moisture content requires less energy for ignition among similar fuel size classes (Thonicke *et al.* 2001; Chuvieco *et al.* 2004). Fires also spread faster as fuel moisture content decreases (Thonicke *et al.* 2001). Modification of fuel moisture content with *B. tectorum* invasion probably also results in a lengthening of the wildfire season. Annual grass-invaded plant communities in our study were dry enough to burn ~1 to 1.5 months earlier than were non-invaded plant communities (Fig. 1). This supports previous observations that *B. tectorum* appears to mature and dry out earlier than does native vegetation in these ecosystems and thus lengthens the fire season (Keeley 2000; Keane *et al.* 2008; Rice *et al.* 2008). The fuel moisture of extinction (fuel moisture content at which fire will not spread) typically ranges from 20 to 24% varying by wind speed in grasslands (Cheney *et al.* 1998). Based on the higher fuel moisture of extinction estimate, the invaded plant communities could burn in late June and early July of 2010 and 2011. In contrast, the non-invaded communities did not dry below the moisture of extinction until early August 2010 and late August 2011. An addition of a month to a month and half when fuels can burn would increase the fire season 1.5- to 2-fold in these plant communities depending on yearly climatic events. Elongated wildfire seasons with *B. tectorum* invasion may further promote fire returns that would be more frequent than historical fire regimes, because ignition sources could make contact with combustible fuels at more times of the year. Earlier season burns may further reduce remaining native bunchgrasses, which are generally more susceptible to earlier fires (Wright and Klemmedson 1965; Britton *et al.* 1990; Davies and Bates 2008).

Greater fine fuel accumulations with invasion may also increase the probability of fire-induced mortality in native perennial bunchgrasses. Increased fuel accumulations around perennial grasses increase the probability of their mortality during fires (Davies *et al.* 2009, 2010; Zimmermann *et al.* 2010). Fuel accumulations around perennial grasses increase soil heating, which elevates the vulnerability of perennial grasses to fire (Odion and Davis 2000).

Bromus tectorum-invaded plant communities may also be more likely to support fires that result in few unburned patches within the burn perimeter because of the increase in fine fuel continuity and amount. These results support hypotheses by Brooks (2008) and Brooks and Chambers (2011) that *B. tectorum* invasion of sagebrush communities supports larger, more contiguous fires. Consistent with our results, Waldram *et al.* (2008) reported that increased fuel loads and continuity caused large fires with fewer unburned patches in Africa. When non-invaded plant communities burn, they would be more likely to produce a mosaic of burned and unburned areas because of discontinuous fuels. A mosaic of burned and unburned plant communities creates a diversity of habitats to meet the needs of multiple species and, thereby, promotes biodiversity at multi-trophic levels (Martin and Sapsis 1992; Panzer 2003). Thus, *B. tectorum* and other exotic annual grasses may be homogenising plant communities, especially post-fire, and potentially higher trophic levels as habitat diversity becomes limited (Knick *et al.* 2003; Davies 2011).

Conclusions

Invasion by *B. tectorum* greatly alters the fuel characteristics of sagebrush plant communities. *Bromus tectorum*-invaded plant communities compared with non-invaded communities have multiple fuel characteristics that may promote frequent, large-scale, fast spreading wildfires. The potential for an increase in fire frequency combined with fuel characteristics that facilitate earlier season wildfires and increased fine fuel loads around perennial grass crowns may increase the susceptibility of perennial grasses to fire. *Bromus tectorum* invasion appears to increase the risk of fire by potentially expanding the wildfire season and producing fuels that may be more likely to combust and propagate a fire. Results from our study demonstrate that the fuel characteristic differences between *B. tectorum*-invaded and non-invaded plant communities are large, revealing the need for research to determine methods to mediate and reverse these invasion associated changes. Additional longer-term research is needed to determine the full effects of *B. tectorum* invasion. In addition, research is needed that incorporates fire treatments into the study design to quantify the effects of the interaction between *B. tectorum* and fires.

Acknowledgements

The authors thank Savannah Duff, Brandi Carlon, Sarah Fitzpatrick, Julie Garner and Rodney Johnson for assisting with data collection. The authors are also grateful to Dustin Johnson and Matt Madsen for reviewing earlier versions of this manuscript. Constructive reviews by anonymous reviewers and the Associate Editor were also appreciated. The Eastern Oregon Agricultural Research Center is jointly funded by USDA – Agricultural Research Service and Oregon State University.

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