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Introduced annual grass increases regional fire activity across the arid western USA (1980–2009)

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Abstract

Non-native, invasive grasses have been linked to altered grass-fire cycles worldwide. Although a few studies have quantified resulting changes in fire activity at local scales, and many have speculated about larger scales, regional alterations to fire regimes remain poorly documented. We assessed the influence of large-scale *Bromus tectorum* (hereafter cheatgrass) invasion on fire size, duration, spread rate, and interannual variability in comparison to other prominent land cover classes across the Great Basin, USA. We compared regional land cover maps to burned area measured using the Moderate Resolution Imaging Spectroradiometer (MODIS) for 2000–2009 and to fire extents recorded by the USGS registry of fires from 1980 to 2009. Cheatgrass dominates at least 6% of the central Great Basin (650 000 km²). MODIS records show that 13% of these cheatgrass-dominated lands burned, resulting in a fire return interval of 78 years for any given location within cheatgrass. This proportion was more than double the amount burned across all other vegetation types (range: 0.5–6% burned). During the 1990s, this difference was even more extreme, with cheatgrass burning nearly four times more frequently than any native vegetation type (16% of cheatgrass burned compared to 1–5% of native vegetation). Cheatgrass was also disproportionately represented in the largest fires, comprising 24% of the land area of the 50 largest fires recorded by MODIS during the 2000s. Furthermore, multi-date fires that burned across multiple vegetation types were significantly more likely to have started in cheatgrass. Finally, cheatgrass fires showed a strong interannual response to wet years, a trend only weakly observed in native vegetation types. These results demonstrate that cheatgrass invasion has substantially altered the regional fire regime. Although this result has been suspected by managers for decades, this study is the first to document recent cheatgrass-driven fire regimes at a regional scale.

Keywords: *Bromus tectorum*, exotic grasses, fire frequency, grass-fire cycle, invasive species, MODIS burned-area product, satellite-based fire data

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Introduction

One of the most notorious ecosystem consequences of non-native plant invasions is the alteration of fire regimes (D'Antonio & Vitousek, 1992; Brooks *et al.*, 2004). Increased fire occurrence, intensity, and severity has been observed in association with invasion by buffelgrass in the US southwest and Mexico (Burquez-Montijo *et al.*, 2002) and Australia (Butler & Fairfax, 2003), gamba grass in Australia (Setterfield *et al.*, 2010), Molasses grass and broomsedge in Hawai'i (Tunison *et al.*, 2001), and cogongrass in the US southeast (Lippincott, 2000). This 'grass-fire' cycle is driven by higher

fine fuel biomass, increased flammability of grasses and/or faster postfire recovery of non-native grasses compared to native species. This phenomenon has been identified globally (Balch *et al.*, 2009; Bowman *et al.*, 2009), but is pronounced in semiarid ecosystems with historically low fire occurrence (D'Antonio & Vitousek, 1992; Brooks *et al.*, 2004). One of the most widely cited examples of a novel grass-fire cycle is the fire activity that has followed cheatgrass (*Bromus tectorum*) invasion into the US Great Basin (Mack, 1981; Whisenant, 1990; Knapp, 1996). On the basis of the fire history of 12 sites in southern Idaho, Whisenant (1990) estimated a fire return interval (FRI) of 3–5 years in cheatgrass-dominated rangelands, compared with 60–100 years in native sagebrush (*Artemisia spp.*). Beyond this study, it is not known how fire regimes have changed across the

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current extent of cheatgrass dominance – currently estimated at over 40 000 km² (Bradley & Mustard, 2008) – within 650 000 km² of land area in the Great Basin.

Invasive grasses that alter the fire cycle are known to increase fire size, fire season length, spread rate, numbers of individual fires and likelihood of fires spreading into surrounding native or managed ecosystems (D'Antonio & Vitousek, 1992; Brooks *et al.*, 2004). However, with the exception of fire size (Knapp *et al.*, 1998), these relationships have yet to be evaluated for cheatgrass at a regional scale. Cheatgrass could change the properties of fire regimes through a number of mechanisms. It increases fine fuel continuity (Whisenant, 1990), enabling fire spread (Link *et al.*, 2006). It also increases fine fuel biomass, particularly following wet years (Hull & Pechanec, 1947; Bradley & Mustard, 2005), and may alter micro-meteorological conditions, decreasing surface soil moisture and raising soil temperatures relative to shrublands due to its shallow root system (Prater *et al.*, 2006).

Furthermore, the mechanisms by which cheatgrass alters fire regimes likely interact with climate. For example, cheatgrass cover and biomass vary with climate (Chambers *et al.*, 2007) and are promoted by wet and warm conditions during the fall and spring (Knapp, 1998). Interannual variability in precipitation driven by El Niño cycles creates years with extremely high cheatgrass biomass (Hull & Pechanec, 1947; Bradley & Mustard, 2005) and others with almost none. In native shrub and grassland ecosystems of the arid western United States, high antecedent precipitation has been shown to be one of the strongest predictors of government-registered burned area (1977–2003), even more so than current-year temperature or drought conditions (Littell *et al.*, 2009). The oscillation between wet years that enable substantial grass growth and dry years that desiccate those built-up fuels may create ideal conditions for high fire years, but this hypothesis remains untested for cheatgrass rangelands. Moreover, drier conditions may also make resident shrubs more flammable, particularly if drier than normal conditions follow a wet year where shrub growth was high. Therefore, the coupling of a wet year and a 'drier than normal' year could provide the right climatic oscillation to promote cheatgrass and fires.

The US Great Basin covers over 650 000 km² and supports a large number of endemic species (Kier *et al.*, 2009). Historically, fire has been a rare event in low and mid elevation Great Basin ecosystems and many of the native plant species are not fire-tolerant (Riegel *et al.*, 2006). The loss of native-dominated shrubland ecosystems has been linked to the decline of sagebrush-dependent species such as the Greater Sage grouse,

currently being considered for listing as an endangered species (Crawford *et al.*, 2004; Connelly *et al.*, 2011). In addition, fire driven conversion of shrubland to grassland has been linked to a loss of carbon storage (Bradley *et al.*, 2006; Prater *et al.*, 2006) and available soil water (Obrist *et al.*, 2003; Prater *et al.*, 2006). Cheatgrass-facilitated fire also presents challenges to human populations and agency budgets in the region. The urban wildland interface in the region has grown dramatically (Theobald & Romme, 2007), and the result is millions of dollars in budgeted and unbudgeted expenses related to fire suppression, fuels management, emergency activities, and postfire rehabilitation (Roberts, 1999; Calkin *et al.*, 2005).

Although the introduced grass-fire cycle and its ecological impacts are recognized (D'Antonio & Vitousek, 1992; Brooks *et al.*, 2004), accurate forecasting of fire risk in the Great Basin requires better understanding of how cheatgrass currently alters fire regimes and the interactions between grass-fueled fire and climate. Cheatgrass has not only invaded many ecosystems of the US Great Basin – predominantly big sagebrush (*Artemisia tridentata*) ecosystems (Chambers *et al.*, 2007) but also pinyon-juniper (Barney & Frischknecht, 1974), and to a lesser extent salt desert shrublands (Haubensak *et al.*, 2009). It is more limited in its establishment >1600 m (Sherrill & Romme, 2012), such as in the higher elevations of the pinyon-juniper zone and subalpine shrubland, montane meadows, and the most saline areas of the valley bottoms (alkali flats). In big sagebrush ecosystems, reported FRIs range from 13 to 25 years (Frost 1998) to 150 years (Baker, 2006; Riegel *et al.*, 2006). In pinyon-juniper, fire returns are estimated ~50 years (Riegel *et al.*, 2006) and as high as 200 years (Schmidt *et al.*, 2002). In the lower, hotter desert shrubland ecosystems sometimes called 'salt desert' and typically dominated by salt tolerant species in the Chenopodiaceae (hereafter desert shrubland), less is known about the fire return and fire-sensitivity of these drought- and high salinity-adapted species (Haubensak *et al.*, 2009).

Our overarching prediction is that cheatgrass would increase fire likelihood due to more continuous, drier, and higher fine fuel loads, relative to the shrublands and forests that it has replaced. These fuels will result in both increased fire ignition probability and increased spread. Here, we use Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-based burned area (2000–2009) data and the USGS registry of fire incidents (1980–2009), to determine whether or not cheatgrass increases fire activity across the US Great Basin. Compared with other vegetation types, including montane shrubland, sagebrush steppe, pinyon-juniper, desert shrubland, and agriculture, we document whether or

not cheatgrass-dominated areas: (i) have higher fire frequency (i.e., lower FRI), (ii) larger average fire size and faster fire spread rates, (iii) are more likely to be ignition points for fire spread, and (iv) show shifts in the seasonality and interannual variability in fires.

Materials and methods

Data sources

Great Basin land cover map. To quantify fire differences between land cover classes, we overlaid three fire perimeter datasets (described below) with a regional map of land cover in the Great Basin (Bradley & Mustard, 2008). This regional map includes both the Great Basin and portions of the adjacent Mojave Desert. This map was created based on vegetation phenology derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite at a 1-km spatial resolution. We chose this map for comparison because it includes the major native land cover classes as well as the distribution of cheatgrass as of the late 1990s (which corresponds with the middle of the USGS fire perimeter time series and the beginning of the MODIS burned area time series). Dense stands of cheatgrass 'grassland' were identified based on strong interannual variability in greenness following wet years, although other land cover classes were identified based on average growing season phenology. Field-based surveys defined the training pixels for the creation of this map, and it was further validated using 30 m plot data collected by the EPA southwest re-GAP (USGS, 2004), see Bradley & Mustard (2008) for further details.

Due to the coarse spatial resolution of the land cover map, mixed pixels are common. For example, pixels containing both pinyon-juniper woodland and sagebrush steppe (common along mountain slopes) could be grouped into either pinyon-juniper or sagebrush. Mixed pixels are also common between cheatgrass grassland and sagebrush steppe (Fig. 1a), hence cheatgrass is likely to be a prominent component of many pixels mapped as sagebrush steppe. The most extensive land cover types identified in this map are the focus of this study (cheatgrass, montane shrubland, agriculture, sagebrush steppe, pinyon-juniper, and desert shrubland); alkali meadow and non-vegetated areas were excluded from the analysis.

Montane shrubland is dominated by montane sagebrush (*Artemisia tridentata* ssp. *vaseyana*) and is located at high elevation. At mid-elevation, pinyon-juniper woodland is dominated by *Pinus monophylla* and *Juniperus osteosperma*. In the basins, sagebrush steppe is dominated by basin big sagebrush (*Artemisia tridentata* ssp. *tridentata*) and Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*). In more arid regions, desert shrubland is dominated by either shadscale (*Atriplex confertifolia*) or saltbush (*Atriplex canescens*) in the Great Basin, or by creosote (*Larrea tridentata*) in the Mojave Desert at the southern end of the study area. Cheatgrass invasion to the point of ecosystem dominance is most common in sagebrush ecosystems, although it is increasingly observed in drier desert shrubland communities (Young & Tipton, 1990).

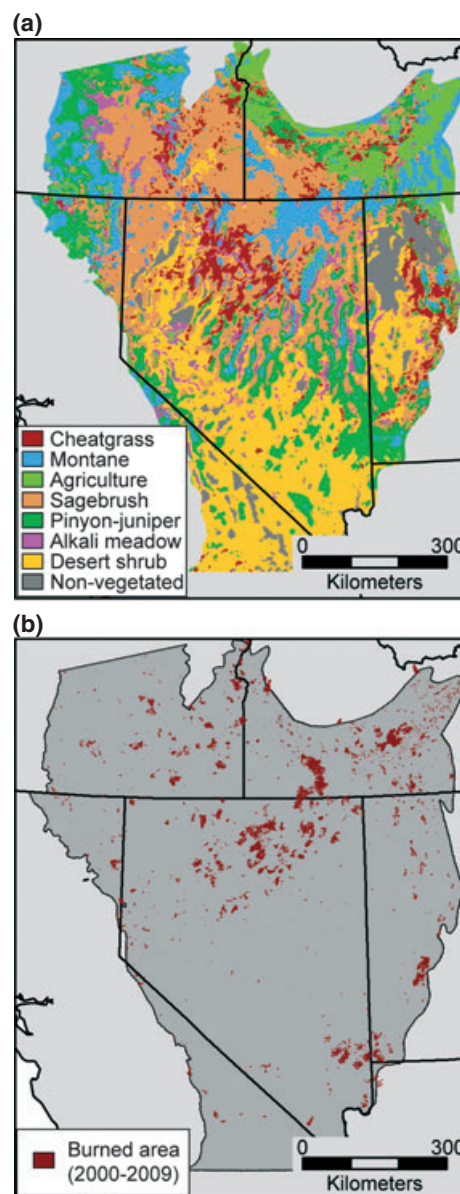


Fig. 1 Illustration of data used to calculate fire statistics for different land cover in the Great Basin. (a) Great Basin land cover using a phenology-based land cover classification from AVHRR satellite time series (Bradley & Mustard, 2008). (b) Burned area from 2000 to 2009 recorded by MODIS.

Cheatgrass invasion is rarer in montane shrubland and pinyon-juniper woodland (Chambers *et al.*, 2007).

Fire data. In this analysis we used the following: (i) 10 years of MODIS burned area data (500 m resolution) from April 2000 to December 2009 (Fig. 1b), (ii) the US Geological Survey historic fire perimeters data (hereafter, USGS) from 1980 to 2007 (Connelly *et al.*, 2004), and (iii) the USGS Rocky Mountain Geographic Science Center fire perimeters data from 2000 to 2009 (hereafter, RMGSC; http://rmgsc.cr.usgs.gov/outgoing/Geomac/historic_fire_data).

The MODIS burned area algorithm uses a signal tracking method that detects changes in reflectance that are interpreted as having had a fire occur, while correcting for illumination-view geometry effects (Roy *et al.*, 2008). Generally, the MODIS burned area product tends to underestimate burned area: smaller fires, or fires that have either a very heterogeneous spatial distribution within the MODIS pixel, have a small effect on the vegetation, or burn where vegetation is very sparse, might not produce a sufficient change in reflectance to be detected (Roy *et al.*, 2008; Chang & Song, 2009; Roy & Boschetti, 2009; Giglio *et al.*, 2010). For example, MODIS burned area estimates for typical savanna landscapes in southern Africa capture approximately 75% of operator-produced estimates using medium resolution optical data, although these figures vary depending on data availability due to cloud cover, angular sampling, and the amount of tree cover (Roy & Boschetti, 2009). In some circumstances, cloudiness preceding and after the date of the fire might reduce the angular sampling of the reflectance, and degrade the continuity of the reflectance time series leading to an undetected burned pixel. We expect the performance of the product over the Great Basin to be comparable to the 75% detection rates measured in Africa because the Great Basin also has low cloud and tree cover. Due to a prolonged instrument outage in June 2001 MODIS burned area data were not included for this month.

In addition to identifying burned area, the MODIS product also reports the date of fire detection (Roy *et al.*, 2005). Under low-cloud circumstances, similar to those found in the Great Basin, the reported day of burn has been shown to be within 1 day of co-located thermal anomaly detections (Boschetti *et al.*, 2010). To delineate fire perimeters from individual burned pixels, we used a flood-fill algorithm to cluster neighboring pixels that burned in close temporal proximity (Archibald & Roy, 2009). In this case, the neighborhood was defined as the eight direct neighbor pixels, and the reported date of fire had to be less than or equal to 2 days to be designated as the same fire event following the findings of Boschetti *et al.* (2010). MODIS' tendency to underreport burning events could cause some larger fires to be split into many smaller ones, which could bias the fire size distribution toward smaller fires.

We also compared fire regimes using the USGS (1980–2007) and RMGSC (2000–2009) historic fire perimeters data. We included the RMGSC data to capture a full dataset to compare with the timeline of the MODIS record. The RMGSC data source contains all fire perimeters that were submitted to the Geospatial Multi-Agency Coordination Group (GeoMAC) by field offices, some data might be missing while other fires might be duplicated. Perimeters are collected in the field by either infrared imagery from airborne sensors or using GPS units on the ground. A known limitation of this data source is that fire reporting has increased through time (Connelly *et al.*, 2004).

In comparison to the MODIS fire product, we expect the burned area calculated within the USGS fire perimeters to be larger, both because MODIS can underestimate burned area (Roy *et al.*, 2008; Chang & Song, 2009; Roy & Boschetti, 2009; Giglio *et al.*, 2010), and because USGS perimeters often do not subtract out unburned islands within the larger perimeters (Fig. 2). We also expect the MODIS product to capture more

small fire events that are less likely to be reported either because they are rapidly extinguished or because they occur on lands that are not an agency (USGS) focus such as agricultural lands.

Quantifying fire statistics on cheatgrass and native land cover

Fire return interval (FRI). For each of the prominent land cover classes, we calculated a FRI, which we define here as the expected number of years between two successive fire events within a given area (Romme, 1980). We calculated the total burned area within each Great Basin land cover class for each of the fire perimeter) datasets by decade (MODIS 2000–2009; USGS 1980–1989, 1990–1999, 2000–2007; RMGSC 2000–2009). We then divided the total burned area by the available land area, as determined by the 1999 land cover map, to determine the proportion that burned annually (or annual fire probability). FRI (in years) is just the inverse of the proportion that burned annually.

Fire size and number of fire events. Separating by decade and data source, we calculated the total number and mean area of individual fires that burned within each land cover class in two ways. For the majority of the calculations (FRI, average fire size, spread rate), we calculated burned area as the area of any single fire event burning on a given land cover class. However, for the purposes of estimating power-law distributions and ignition points (see below), fires that burned across multiple land cover classes were assigned to the land cover with the maximum fraction of cover within the fire perimeter. We compared the resulting fire size distribution for each land cover type using power-law distributions (Clauset *et al.*, 2009), in which the probability of a fire having a size greater than or equal to x , is given by the inverse size raised to a power of α (see Supporting Information Figure S1).

Fire spread rate. On the basis of the MODIS fire product (2000–2009), we calculated the mean fire duration (in days) and the mean fire spread rate (in $\text{km}^2 \text{day}^{-1}$) for each land cover class. Fire duration and spread rate on fires that burned multiple land cover classes were calculated based on the portion burning only on a given land cover class. These metrics could not be calculated from the USGS or RMGSC datasets because fire duration was not recorded.

Fire ignition points. To test whether or not fires were more likely to start on cheatgrass grassland, we used the MODIS fire perimeters for 2000–2009 and calculated the start and end date of each fire. We then selected the fires that burned for more than 1 day (multi-date fires). Next, we identified locations of cheatgrass grassland within each of those multi-date fires and calculated the minimum burn date occurring within cheatgrass. We used this to divide the data into multi-date fires that burned on cheatgrass on their first day and multi-date fires that did not burn in cheatgrass on their first day. We compared the proportion of burn starts in cheatgrass grassland to the fraction of cheatgrass area burned in each multi-date fire.

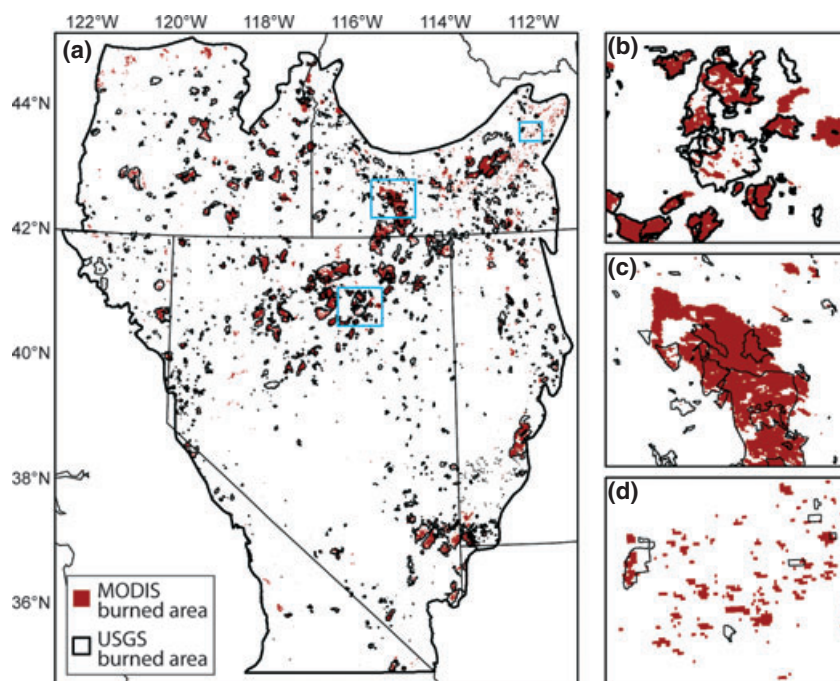


Fig. 2 Comparison of the MODIS and USGS burned area products for 2000–2007 (when the two products overlap). (a) Fire perimeter comparison throughout the Great Basin. Blue squares indicate (from left to right) panels b, c, and d. (b) MODIS burned area tends to be smaller and patchier within the USGS defined fire perimeters. (c) But, occasionally MODIS burned area extends outside of USGS fire perimeters. (d) In particular, MODIS burned area identified numerous small fires in agricultural fields that are not included in USGS fire perimeters.

If fires were not more likely to start on cheatgrass, we would expect fire starts on cheatgrass to be proportional to the available land area of cheatgrass within the fire perimeter.

Fire seasonality and interannual variability. To test whether or not the seasonality of fire is shifted with cheatgrass, we calculated the month with the maximum area burned for each land cover type across the MODIS record. To test the hypothesis that cheatgrass fires are likely to follow wet years, we used the USGS fire perimeter data from 1980 to 2007 to measure interannual variability in fire size and total area burned on cheatgrass relative to native vegetation types. We correlated these results to average annual precipitation from the current and preceding year in the Great Basin for the same time period based on PRISM data (PRISM Climate Group, Oregon State University, <http://prism.oregonstate.edu>; Daly *et al.*, 2002).

Results

Comparison of fire data sources. Overall, the MODIS burned area product overlapped with 64% of the fires delineated by the USGS and 80% of the fires delineated by RMGSC during the 2000–2007 time period. From 2000 to 2007, MODIS recorded a total area burned of 25 045 km² in 7233 unique events, RMGSC recorded a total area burned of 31 983 km² in 1583 unique events, and USGS recorded a total area burned of 41 326 km²

in 3250 unique events. Average fire sizes reported by the USGS and RMGSC products were four to six times greater than the average fire size determined by the MODIS fire size algorithm, with MODIS, USGS, and RMGSC recording fires averaging 3.5, 12.7, and 20.2 km², respectively.

During the three decades of USGS fire perimeter reporting, there is a trend of increasing total burned area and number of fire events: from 1980 to 1989 a total of 16 294 km² burned in 2139 unique events, from 1990 to 1999 a total of 28 484 km² burned in 3232 unique events, and from 2000 to 2007 a total of 41 326 km² burned in 3250 unique events (scaled to a decade this would be 51 657 km² total burned area in 4062 unique events; Fig. 3). This increasing trend in burned area in the USGS record could be explained by increased reporting through time, which has been documented (Connelly *et al.*, 2004). Despite the difficulty of comparing between decades, cheatgrass consistently had the largest total proportional area burned relative to other land cover classes (Fig. 3).

Fire return interval by land cover. Based on MODIS data, 13% of cheatgrass land cover burned from 2000 to 2009 (Table 1). This is more than double the proportional amount that burned in any other vegetation type

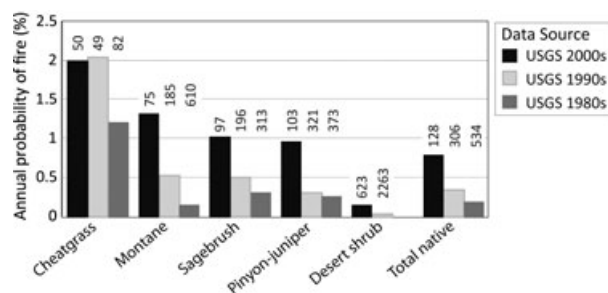


Fig. 3 Annual probability of fire by vegetation type, based on the USGS record 1980–2007. Corresponding FRI values are indicated above each bar.

(range: 0.5–6%): sagebrush (5.1%), desert shrub (0.5%), pinyon-juniper (3.3%), montane shrub (5.9%), and agriculture (6.0%). Relative to available land cover, this burn proportion in cheatgrass corresponds to a FRI of 78 years. FRI for native land cover ranged from 168 to 1946 years: sagebrush (196 years), desert shrub (1946 years), pinyon-juniper (299 years), montane shrub (169 years), and agriculture (168 years). Hence, the cheatgrass FRI was less than half of that observed for sagebrush – the vegetation that it predominantly replaces (Chambers *et al.*, 2007). Across the Great Basin, the cheatgrass FRI was nearly four times more frequent than the average across all native land cover (FRI: 294 years).

Across all three fire datasets (MODIS, USGS, RMGSC), FRI for cheatgrass during the 2000s ranged from 50 to 78 years. Similar to the MODIS record alone, the probability of fires on cheatgrass is much higher than on native land cover regardless of the data source (Fig. 4). Based on all three fire datasets during the 2000s, cheatgrass was two to three times more likely to burn than the total of all Great Basin land cover. Based on the USGS fire dataset in the 1980s and 1990s, cheatgrass was 3.5–4 times more likely to burn than the total of all Great Basin land cover (Fig. 3). Hence, cheatgrass is consistently burning much more

frequently than native land cover regardless of fire dataset or time period.

Fire size. The area (km^2) of individual fire events burning on cheatgrass grassland averaged 4.69 km^2 (± 0.60 SE) based on the MODIS data. Cheatgrass' average fire size was significantly larger than fires on pinyon-juniper ($2.99 \text{ km}^2 \pm 0.33$, SE), montane shrubland ($2.76 \text{ km}^2 \pm 0.35$), and agriculture land cover classes ($0.82 \text{ km}^2 \pm 0.08$), but was not significantly larger than the sagebrush steppe ($4.65 \text{ km}^2 \pm 0.61$) or desert shrub ($3.52 \text{ km}^2 \pm 1.00$) (Table 2). Fire size statistics varied considerably between fire products due to the USGS and RMGSC fire perimeters' tendency to estimate larger fire extents than MODIS. However, fires burning on cheatgrass grassland were consistently the largest or second largest regardless of fire data source or decade (burned area records for all datasets and time periods are shown in Table S1).

Of the 50 largest fire events in the MODIS dataset (2000–2009), 39 were associated with cheatgrass cover. A total of $11\,842 \text{ km}^2$ of land burned in the 50 largest fire events (nearly half the land area of all 8385 fire events, which totaled $26\,445 \text{ km}^2$). Of this, cheatgrass grassland comprised an area of 2867 km^2 , or 24% of the total area burned in large fires. Given that cheatgrass cover comprises only 6% of the landscape, and 13% of total land area burned from 2000 to 2009, cheatgrass was disproportionately represented among the largest fire events.

Cheatgrass fire frequency and fire size (km^2) both varied considerably interannually (Fig. 5). Over the 1980–2007 USGS time series, precipitation during the preceding calendar year was strongly correlated with both cheatgrass fire size ($R^2 = 0.27$) and number of fires ($R^2 = 0.22$), whereas current year precipitation was not. In fact, for all native land cover classes, current year precipitation was not significantly correlated with fire size or area. The correlation between antecedent precipitation and fire number and area was much stronger in cheatgrass than that in

Table 1 Summary of burned area and fire probabilities by land cover class for 2000–2009 based on the MODIS burned area product. Relative FRI is relative to that observed for cheatgrass

Land cover	Burned area (km^2)	Land cover area (km^2)	Annual probability of fire	FRI (years)	Relative FRI
Cheatgrass grassland	5258	41 208	0.0128	78	1.0
Sagebrush steppe	8884	173 803	0.0051	196	2.5
Desert shrubland	757	147 302	0.0005	1946	24.9
Pinyon-juniper	3427	102 533	0.0033	299	3.8
Montane shrubland	4634	78 353	0.0059	169	2.2
Agriculture	2952	49 480	0.0060	168	2.1
Total native land cover	17 961	528 263	0.0034	294	3.8

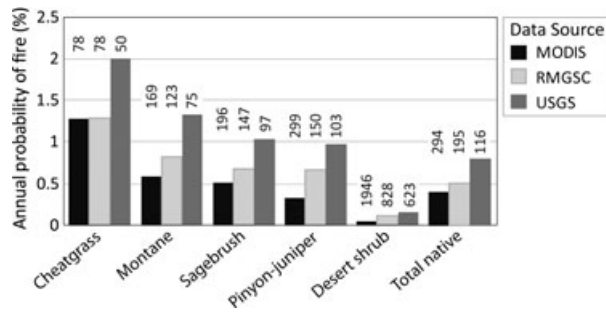


Fig. 4 Annual probability of fire by vegetation type, comparing MODIS (2000–2009), RMGSC (2000–2009), and USGS (2000–2007). Corresponding FRI values are indicated above each bar.

native land cover classes. Preceding year's precipitation explained 12% of variation in sagebrush fire size ($R^2 = 0.12$) and 13% of the variation in number of sagebrush fires ($R^2 = 0.13$). Montane shrubland, pinyon-juniper, and desert shrub had poor correlations to preceding precipitation for both fire size ($R^2 = 0.02$, $R^2 = 0.09$, and $R^2 = 0.03$ respectively) and number of fires ($R^2 = 0.02$, $R^2 = 0.06$, and $R^2 = 0.06$, respectively).

Comparison of the power-law distributions (Figure S1 and Table S2) suggests that the overall fire size distributions for cheatgrass, pinyon-juniper, sagebrush steppe, and desert shrub are not different (alphas = 1.45–1.48), whereas the distributions for montane shrub, and agriculture have increasing alpha values, suggesting that large fires are rarer with respect to small ones. Most notable is the change in distribution of agricultural fires (alpha = 1.7), relative to the sagebrush that it presumably replaced. Agricultural fires are clearly smaller and more frequent, and there are no extremely large agricultural fire events ($>100 \text{ km}^2$).

Fire duration and spread rate. Based on the MODIS dataset, cheatgrass fires are estimated to burn longer [3.07 ± 0.09 (SE) days] than all other land cover types, which may be due to greater individual fire size. Fire duration was significantly longer than that on all other land cover types except

for desert shrub (Table 2), although note that only a small proportion of desert shrub burned during this decade (0.5%). Cheatgrass fires were most likely to burn during the month of July, which was similar to sagebrush, but later than pinyon-juniper and desert shrubland and earlier than montane shrubland and agriculture. Cheatgrass fires had an average spread rate of 0.75 ± 0.06 (SE) $\text{km}^2 \text{ day}^{-1}$, which was not significantly different from desert shrubland ($0.67 \pm 0.13 \text{ km}^2 \text{ day}^{-1}$) or sagebrush ($0.78 \pm 0.06 \text{ km}^2 \text{ day}^{-1}$), but was significantly faster than fires on pinyon-juniper ($0.62 \pm 0.04 \text{ km}^2 \text{ day}^{-1}$), montane shrubland ($0.54 \pm 0.04 \text{ km}^2 \text{ day}^{-1}$) and agriculture ($0.30 \pm 0.01 \text{ km}^2 \text{ day}^{-1}$; Table 2).

Fire ignition points. Multi-date fires (MODIS) are significantly more likely to have burned in cheatgrass cover on their first day compared to other vegetation types. There were 471 multi-date fires in the Great Basin MODIS record (2000–2009) that included some cheatgrass grassland (18% of all multi-date fires recorded by MODIS). Of the multi-date fires that included cheatgrass, 379 contained multiple land cover classes (the rest were 100% cheatgrass). Of these, 65% burned cheatgrass on the first day ($N = 247$). If fires were equally likely to start on cheatgrass as on any other land cover type, we would expect fire starts on cheatgrass to be proportional to land area of cheatgrass within the total fire perimeter. However, fires were much more likely to have started on cheatgrass relative to the available land area of cheatgrass within each fire perimeter (Fig. 6).

Discussion

Our data provide the first quantitative, basin-wide support for the widespread belief that cheatgrass increases fire activity across the Great Basin. This conclusion is consistent regardless of the fire dataset chosen for the analyses (MODIS vs. USGS vs. RMGSC). We found that

Table 2 Summary (and standard errors in parentheses) of average fire area, duration, spread rate, and peak burn month by land cover class based on the MODIS burned area product (2000–2009)

Land cover	N fires	Average area (km^2)	Average duration (days)	Fire spread rate ($\text{km}^2 \text{ day}^{-1}$)	Max burn month
Cheatgrass grassland	1122	4.69 (0.60)	3.07 (0.09)	0.75 (0.06)	July
Sagebrush steppe	1910	4.65 (0.61)	2.70 (0.06)**	0.78 (0.06)	July
Desert shrubland	215	3.52 (1.00)	3.02 (0.18)	0.67 (0.13)	June
Pinyon-juniper	1145	2.99 (0.33)**	2.83 (0.08)*	0.62 (0.04)*	June
Montane shrubland	1681	2.76 (0.35)**	2.69 (0.06)**	0.54 (0.04)**	August
Agriculture	3616	0.82 (0.08)**	2.18 (0.04)**	0.30 (0.01)**	September
Total native land cover	4752	3.83(0.37)	2.40 (0.03)	0.72 (0.04)	July

*Significantly different from cheatgrass at 90% CI.

**Significantly different from cheatgrass at 95% CI.

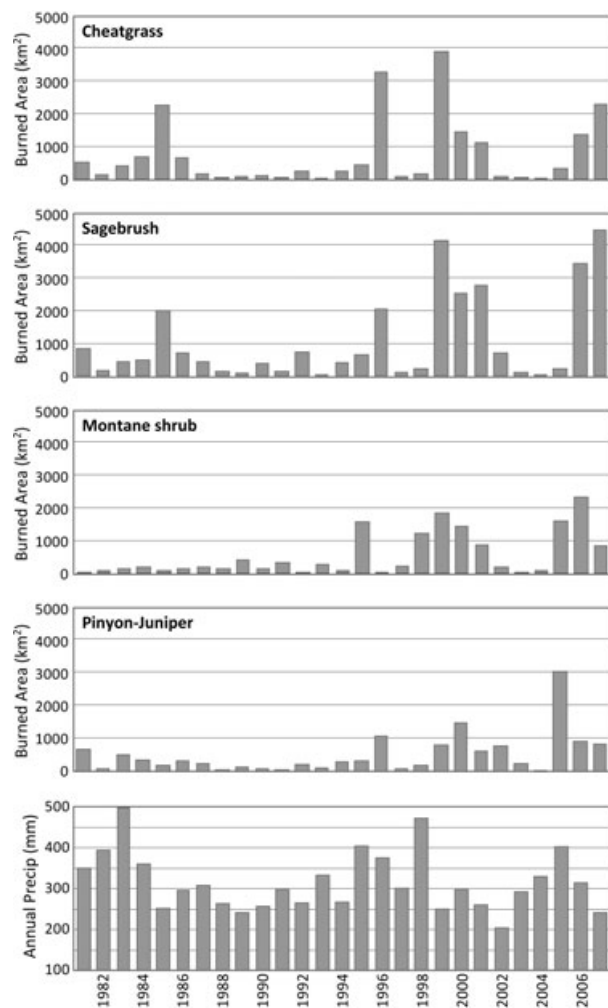


Fig. 5 Interannual variability in total burned area (USGS: 1980–2007) by vegetation type (top four panels) and average annual precipitation (Daly *et al.*, 2002) across the US Great Basin.

fires were more likely to start in cheatgrass than in other vegetation types and that cheatgrass is associated with increased fire frequency, size, and duration.

Comparison of fire data products. MODIS fire perimeters overlapped with 64% and 80% of fires identified by USGS and RMGSC, respectively. There are however, notable differences in reported fire size and number. For example, between 2000 and 2007, average recorded fire size was 3.5 km² (MODIS) and 12.7 km² (USGS), and the number of unique fire events was 7233 (MODIS) and 3250 (USGS) ($N = 3250$). These differences likely stem from problems of both excessive splitting (MODIS) and underreporting (USGS and RMGSC). MODIS excludes the unburned islands within a fire perimeter (which may also lead to further splitting of fires that should be lumped), and records small fires ~0.25 km² (i.e., single pixel fires). On the other hand,

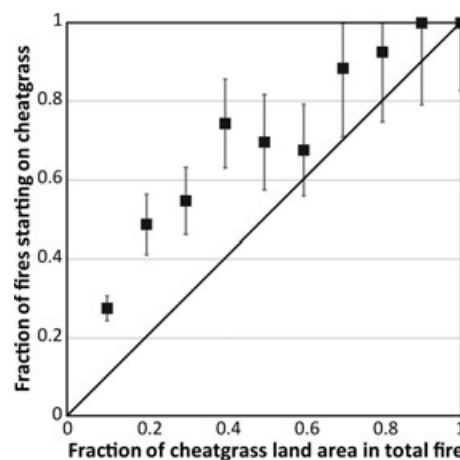


Fig. 6 Fraction of cheatgrass cover within a fire that crosses multiple vegetation types vs. the fraction of fires starting on cheatgrass (based on MODIS). Points with 95% confidence intervals above the 1 : 1 line show where cheatgrass is more likely to be among the first land cover burned than would be predicted by its proportional area within multi-date fire perimeters.

the two USGS products capture an entire fire perimeter, likely ignoring burn patchiness, and tend to underreport small fires and those on lands that are not an agency focus (e.g., agricultural lands). We found no reason, however, to suspect that any of the fire perimeters over or underrepresent fires on a particular land cover type (with the exception of agriculture). Cheatgrass and native land cover classes show similar ranked order of fire probability regardless of the product used (cheatgrass highest, desert shrubland lowest; Fig. 4). Also, despite differences in number and size of recorded fires, our conclusions regarding cheatgrass influences on fire regime are robust.

Cheatgrass alteration of fire regimes. Cheatgrass-dominated rangelands were nearly four times more likely to burn than native land cover during the 2000s based on the MODIS dataset (Table 1). This increased fire frequency corresponds to a FRI of 78 years on cheatgrass grassland (Fig. 3). In comparison, FRI for all native land cover was 294 years based on MODIS, although the climatic suitability and invasion potential differs substantially across Great Basin ecosystems. Of the ecosystems that cheatgrass predominantly invades – sagebrush steppe, pinyon-juniper, and desert shrub – FRIs were 2.5, 3.8, and 24.9 times longer than those documented for cheatgrass. These results demonstrate a clear increase in fire frequency associated with cheatgrass invasion, and is demonstrated across vegetation types and the three data sources used.

The range of FRIs measured for cheatgrass (49–78 years; across all three data sources) is consider-

ably longer than the 3–5 years measured by Whisenant (1990). This widely cited estimate may be particularly low because cheatgrass is abundant in the Idaho study area, ignition sources are prevalent, and soils and microclimate support cheatgrass growth every year there. In contrast, our observations span the Great Basin and thus include regions that vary widely in ignition sources and frequencies, cheatgrass fuel characteristics, and other topographic and climatic factors influencing fire occurrence. Areas with very likely cheatgrass-facilitated fire, such as the one studied by Whisenant (1990), do not appear to be the norm for the entire region, although they point to a likely scenario where cheatgrass biomass and ignition sources are high. Our FRIs also may tend to be low because we based them solely on vegetation dominated by cheatgrass. Shrublands that burned during the time period may have had a cheatgrass understory, but because we have no current way of detecting this, we cannot correct for this cheatgrass contribution to FRI.

Fire return interval in the other Great Basin ecosystems are similarly longer than those reported elsewhere (Frost 1998, Baker, 2006; Riegel *et al.*, 2006). In big sagebrush ecosystems (MODIS FRI estimate = 196 years), reported FRIs range from 13 to 25 years (Frost 1998) on the low end to 150 years on the higher end (Baker, 2006; Riegel *et al.*, 2006). In pinyon-juniper (MODIS FRI estimate = 299 years), fire returns are estimated ~50 years (Riegel *et al.*, 2006) and as high as 200 years (Schmidt *et al.*, 2002). It is important to note that field-based estimates of FRI may vary widely even within vegetation types due to natural site variation in climate and/or productivity. More arid, less productive sites would burn less frequently than wetter, more productive sites due to lower fuel production and could result in FRIs that ranged from decades to centuries, as observed for sagebrush steppe and juniper woodlands (Miller & Heyerdahl, 2008). Direct comparison of remotely sensed and fire history derived FRIs may be limited due to differences in scale and methodology. Our longer estimates of fire return times may also be the result of using only a decade of MODIS data that may not capture multi-decadal climate oscillations that can strongly influence western US fire activity (Kitzberger *et al.*, 2007), or multi-century, stand-replacing fire events (Bauer & Weisberg, 2009).

Fire size, duration, and spread rate in cheatgrass grassland were among the largest of those measured for any land cover type (Table 2). However, cheatgrass fires were not significantly different from fires burning on sagebrush or desert shrubland, and their fire size distributions are similar (Figure S1). Furthermore, cheatgrass did not sustain an earlier fire season; the month of peak burning was July for both cheatgrass

and sagebrush and June for desert shrub across the MODIS record (2000–2009). However, these are the two native ecosystems that cheatgrass primarily invades, and the land cover classification does not distinguish this mixing (Bradley & Mustard, 2008). Hence, elevated fire size, duration, spread, and timing within sagebrush and desert shrubland may also be caused by cheatgrass invasion that was undetected in the land cover map used in this analysis (Bradley & Mustard, 2008). Furthermore, this would result in our estimates of the cheatgrass FRI being higher than might be expected if actual cheatgrass cover was known within the shrubland vegetation types as noted above. The notably long the cheatgrass FRI in desert shrub (FRI = 1946), yet similar fire size, duration, and spread to cheatgrass fires may point to substantially cheatgrass-influenced fires in desert shrub, which has been documented in north-west Nevada (Haubensak *et al.*, 2009). Cheatgrass fires were significantly larger, longer and faster on average than fires in pinyon-juniper and montane shrubland. This finding is consistent with hypotheses that increased availability of fine fuels allows cheatgrass fires to spread farther (Knapp, 1998). As a result, grass fires burning primarily in cheatgrass and sagebrush have become the dominant source of fire in the region (Table 2; Fig. 4).

Agriculture is also a notable fire source, with numerous small fires burning in agricultural fields. There is a clear shift in the fire size distribution to more frequent and smaller fires, and the peak burning month (September) is much later. The source of these fires is likely anthropogenic burning of field residues following harvest. This additional anthropogenic influence may pose a further management challenge due to the increased ignition sources and adjacency to cheatgrass areas.

Cheatgrass grassland is also strongly linked to the largest MODIS-recorded fires (2000–2009), and serves as a primary ignition point. Influencing 39 of the 50 largest fire events, cheatgrass comprised 24% of the total land area burned, which was disproportionately larger than both the available land area of cheatgrass (6%) and the area burning across all Great Basin fires (3%). Sagebrush steppe, which is heavily invaded by cheatgrass, is also disproportionately represented in these largest fires, indicating that grass-shrubland fires represent the greatest hazard for fire management. Cheatgrass was also more likely to be the ignition point, with significantly more cheatgrass pixels burning on the first day of fires than would be expected given the available land area of cheatgrass (Fig. 6). Hence, cheatgrass is not only a carrier of fire due to elevated fine fuel biomass (Knapp, 1998; Link *et al.*, 2006) but is also highly flammable and likely to ignite. Although it is not certain how the total density and distribution of

lightning and anthropogenic ignitions vary, 60% of registered fires (2001–2011) in the Great Basin were human ignited (NIFC, 2012). Cheatgrass is also closely associated with roads (Mack, 1981; Bradley & Mustard, 2006), which is where anthropogenic ignitions are likely. The influence of cheatgrass on the largest fires and likelihood of catching fire are of clear interest to fire management agencies in the Great Basin where protecting remaining habitat as well as keeping fire out of the urban-wildland interface are key priorities (Chambers & Wisdom, 2009).

Fire occurrence and climate. Total burned area shows substantial interannual variability across all Great Basin land cover classes (Fig. 5), which is partially explained by total precipitation in the preceding calendar year. This correlation is strongest for cheatgrass and sagebrush. Strong interannual variability in cheatgrass cover and biomass has been noted previously in shrubland settings (Hull & Pechanec, 1947; Chambers *et al.*, 2007), particularly in the absence of native shrubs (Chambers *et al.*, 2007), and linked to elevated winter precipitation during El Niño events (Bradley & Mustard, 2005). These results suggest that elevated cheatgrass biomass following El Niño events is strongly linked to increased risk of fire during the following years' summer.

Future projections of climate change suggest that the western United States is likely to become warmer and have greater precipitation variability, which could increase or decrease cheatgrass fire probability depending on how much warmer temperatures influence moisture availability. In the northern Great Basin, precipitation is projected to increase during the winter and early spring months most critical for cheatgrass growth (IPCC, 2007; Abatzoglou & Kolden, 2011). Based on fire size correlations with precipitation, these changes could have the greatest influence on cheatgrass biomass and corresponding fire cycles as antecedent precipitation is a strong predictor of fire in grass systems (Littell *et al.*, 2009). At the same time, warmer temperatures and drought have been shown to increase fire frequency and size in forests across the western United States (Westerling *et al.*, 2006; Littell *et al.*, 2009). Here, we have documented that cheatgrass-dominated areas, which currently cover ~40 000 km², sustain increased fire probability compared with native vegetation types. As sites burn, more and more of them are likely to become cheatgrass grasslands thus increasing their future probability of burning. If future climate scenarios hold true, the combination of warmer temperatures and high water availability could yield larger fire events that are carried between forested or shrubland areas by invasive grasses, thus perpetuating a novel

grass-fire cycle across the western United States and ultimately reducing cover of woody species.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Table S1. Number of fires and fire size by land cover type for each of the three data sources for the 2000s and for the three decades recorded by USGS.

Table S2. Power-law model fit parameters and statistics.

Figure S1. Cumulative probability $P(x)$ of a fire event (x) being greater than or equal to a given size vs. fire size (log).

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