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Postfire Downy Brome (*Bromus tectorum*) Invasion at High Elevations in Wyoming

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The invasive annual grass downy brome is the most ubiquitous weed in sagebrush systems of western North America. The center of invasion has largely been the Great Basin region, but there is an increasing abundance and distribution in the Rocky Mountain States. We evaluated postfire vegetation change using very large–scale aerial (VLSA) and near-earth imagery in an area where six different fires occurred over a 4-yr period at elevations ranging from 1,900 to over 2,700 m. The frequency of downy brome increased from 8% in 2003 to 44% in 2008 and downy brome canopy cover increased from < 1% in 2003 to 6% in 2008 across the entire study area. Principal component analyses of vegetation cover indicate a shift from plant communities characterized by high bare soil and forbs immediately postfire to communities with increasing downy brome cover with time after fire. The highest-elevation sampling area exhibited the least downy brome cover, but cover at some midelevation locations approached 100%. We postulate that the loss of ground-level shade beneath shrubs and conifers, accompanied by diminished perennial vegetative cover, created conditions suitable for downy brome establishment and dominance. Without a cost-effective means of landscape-scale downy brome control, and with infestation levels and climate warming increasing, we predict there will be continued encroachment of downy brome at higher elevations and latitudes where disturbance creates suitable conditions.

Nomenclature: Downy brome, *Bromus tectorum* L.

Key words: Wildfire, climate change, annual grass invasion, invasive species, high-elevation rangelands, cheatgrass.

Downy brome or cheatgrass (*Bromus tectorum* L.) spread across most of the western United States by 1930 (Mack 1981), and now affects at least 22.5 million hectares (56 million acres) in the United States (Duncan et al. 2005). Infestations produce abundant and often continuous cover that dries in early summer to a highly flammable fine fuel (D'Antonio and Vitousek 1992; Link et al. 2006; Whisenant 1990). Its growth is enhanced by increased nutrient availability following fires, whereby it establishes a downy brome–wildfire cycle that has shortened the historical fire return intervals of 30 to 50 yr to 3 to 5 yr (Whisenant 1990). As a result, vast portions of the western United States are in an alternative stable state dominated by downy brome that precludes succession to a more desirable species composition (Brown et al. 2009).

Although downy brome may be utilized as early spring livestock forage, its suitability as such is debatable (Young and Clements 2007) largely because of its brief period of palatability and unpredictability from year to year. Downy brome production is highly dependent on annual precipitation (Ganskopp and Bedell 1979), complicating grazing management. Downy brome–driven wildfires present ranchers with economic losses in addition to forage losses through downy brome replacement of desirable species (Maher 2007). Although downy brome readily invades disturbed areas, it has been recorded in relatively undisturbed areas such as isolated kipukas and ungrazed islands (Kindschy 1994; Tausch et al. 1994).

Researchers and resource managers are concerned that warming trends may lead to an increased susceptibility to invasion and dominance of exotic plants at higher elevations in Wyoming (Smith and Enloe 2006) and elsewhere (Pauchard et al. 2009). Although it has been present in Wyoming since the early 1900s, in recent years downy brome has increased its distribution, notably in the higher-elevation western counties (Wyoming Pest Detection Program 2010). Downy brome populations have been recorded at high elevations in the Rocky Mountains

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Management Implications

The annual grass known as downy brome or cheatgrass is one of the worst weeds of western North America infesting nearly 23 million hectares, reducing rangeland forage and habitat value and increasing wildfire risk. Downy brome is not only expanding across the landscape, but is also expanding to higher elevations, spreading the fire risk from sagebrush lowlands into higher-elevation rangeland systems. Downy brome cover in the foothills of the southern Wind River Mountains at elevations of 1,900 to 1,700 m averaged $< 1\%$ in 2002, but expanded to $> 6\%$ cover by 2008, approaching 100% cover at some individual sites. Local spring temperatures have increased into the range that supports early downy brome growth. We speculate that fire removed shading overstory, further increasing spring soil temperatures to allow downy brome to rapidly expand. Concurrently, longer, drier growing seasons are reducing native plant growth and competitiveness. We recommend that land managers be aware of the risk of downy brome expansion at higher elevations and adjust their management to address postfire downy brome infestations.

(2,700+ m [8860+ ft]; Bromberg et al. 2011; Brown and Rowe 2004) and in California (2,500 m [8200 ft]; Gerlach et al. 2003; Keeley and McGinnis 2007), but Bradley and Mustard (2006) suggest a near 0% probability of downy brome invasion at elevations higher than 2,500 m in the Great Basin. Although these reports indicate the ability of downy brome to establish self-sustaining populations at high elevations, little evidence documents change in downy brome abundance at high elevations following wildfire. A thorough understanding of postfire invasion dynamics at high elevations is needed to assist land managers in prioritizing fire rehabilitation and weed control efforts.

Downy brome seeds readily germinate during low temperatures of fall, winter, or early spring (< 5 C [41 F]) resulting in seedling emergence in large numbers ranging from 1,960 to over 14,000 seedlings/m^2 (Buman and Abernethy 1988; Hull and Hansen 1974; Martens et al. 1994; Wilson et al. 1974). Once germinated, downy brome seedlings develop quickly at cool temperatures relative to other grass species (Aguirre and Johnson 1991). These observations indicate downy brome's ability to germinate at the freeze–thaw boundary typical of areas where snow-cover duration is being reduced, and snowmelt and runoff (and by implication, soil desiccation) are occurring earlier in the year.

Observed and predicted warming trends at temperate latitudes may further exacerbate downy brome invasion at high elevations. Multiple models indicate high-expansion risk in Wyoming under various climate change scenarios (Bradley 2009). Many indications of warming trends come from mountain environments where measures of climate change are often amplified relative to change indicators from lower elevations (Beniston et al. 1997; Pepin and Lundquist 2008). Decreased duration of snow cover (Brown 2000; Brown and Mote 2009), earlier and abbreviated spring runoff (Stewart et al. 2004), decreased proportion of snow to rain (Nayak et al. 2010), and earlier soil warming (Day 2009) may all contribute to upslope migration of vascular plants, including downy brome, as temperatures increase (Parolo and Rossi 2008).

Given that downy brome germinates and establishes at temperatures near the freeze/thaw threshold and that mountain ecosystems have warmed and are predicted to warm further, we sought to evaluate the potential for fire-mediated downy brome expansion in such environments. The objectives for this study were to (1) document short-term, postfire vegetation dynamics in relatively high-elevation areas (1,900 to 2,670 m) of sagebrush grassland and within coniferous forest of the east slope of Wyoming's Wind River Range (part of the Rocky Mountain cordillera) and (2) evaluate the utility of image-based monitoring for documenting downy brome populations in remote, topographically diverse landscapes.

Materials and Methods

Study Site. The study site was located in central Wyoming in the southern Wind River Mountains at 1,900 to 2,700 m in the foothills and mountains east of Lander, WY, in the 250- to 350 mm (9.8–13.7 in) precipitation zone (Figure 1). Precipitation during the span of our study was variable among the years of vegetation sampling, and during the periods of time prior to sampling (Figure 2). Native vegetation includes plant communities such as mountain shrub/perennial grass, Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young)/perennial grass, mountain big sagebrush [*Artemisia tridentata* Nutt. subsp. *vaseyana* (Rydb.) Beetle]/perennial grass, lodgepole pine (*Pinus contorta* Douglas ex Louden), and others. Multiple wild or prescribed fires burned the area between 1993 and 2002 (Figure 1). The only burn to have any reseeding was the Commissary Hill fire (East Burn), which was seeded with bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve] (5.6 Pure Live Seed (PLS) kg ha^{-1} [5 lb ac^{-1}]), Idaho fescue (*Festuca idahoensis* Elmer) (2.2 PLS kg ha^{-1}), and antelope bitterbrush [*Purshia tridentata* (Pursh) DC] (2.2 PLS kg ha^{-1}) and all burns were deferred from domestic livestock grazing for two growing seasons.

Image Acquisition. *Sample Locations.* Vegetation was sampled using ~ 1 mm ground sample distance (GSD) aerial and ground-based imagery at a total of 130 locations throughout the study site. Limestone Mountain and Young Mountain were sampled in 2002 (2 and 1 yr postfire, respectively), and again in 2003. Pass Creek was sampled in 2003 (1 yr postfire). All areas were again sampled in 2008.

Aerial Imagery. We acquired VLSA imagery in 2002, 2003, and 2008 (Table 1). VLSA images are nadir, intermittent,

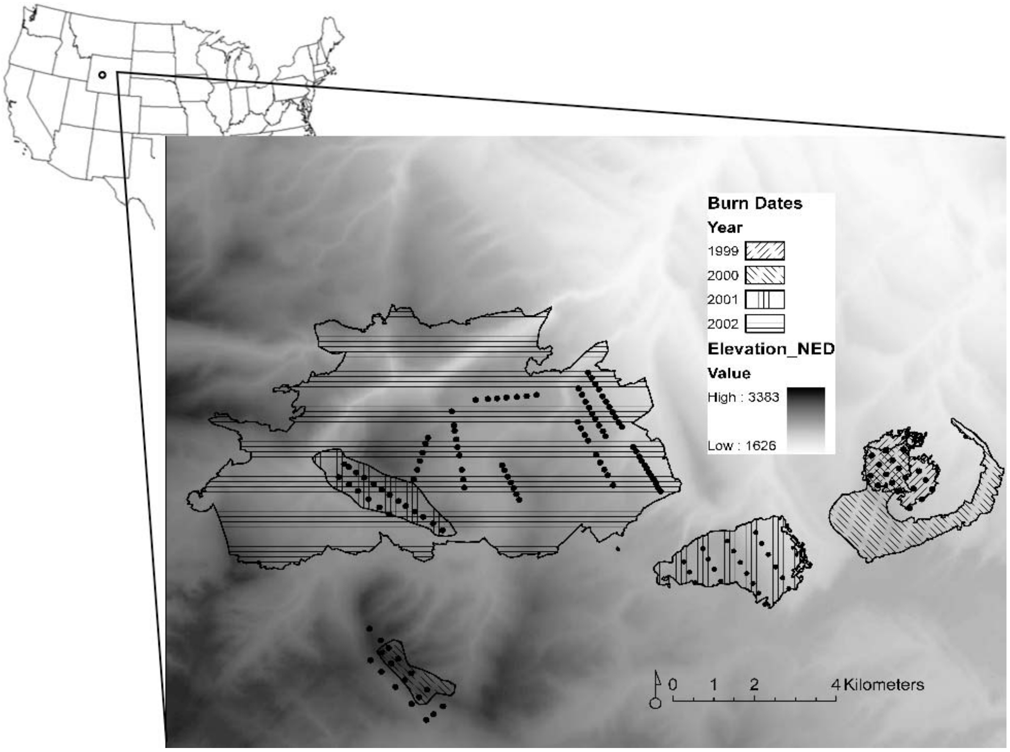

Figure 1. Vegetation sampling locations and burned areas within the Red Canyon study site near Lander, WY. Dots indicate image acquisition (sampling) locations and polygons represent fire boundaries from 1993 to 2002, all overlaying digital elevation data for the site.

high-resolution samples of the landscape, and as such do not provide continuous image coverage. Common to all 3 yr of collection was a three-axis light sport airplane (FAA 2007) equipped with a navigation- and camera-triggering system and a laser rangefinder for measuring airplane altitude above ground level (AGL) (Booth and Cox 2008).

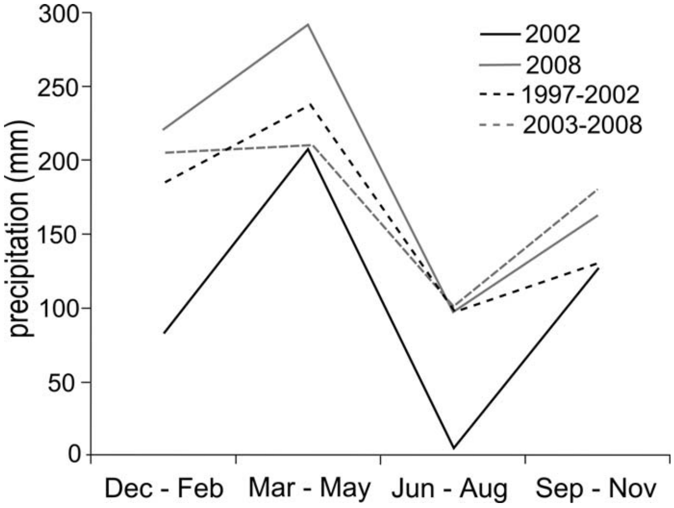

Figure 2. Mean precipitation (mm) for vegetation sampling years (2002, 2008) and 6-yr periods prior to and including sampling years from the South Pass Snotel site (~ 24 km from center of study area) for 3-mo increments approximating winter, spring, summer and autumn.

In 2002 we acquired 70 mm, 1:200 scale natural color images from 100 m AGL using a Hulcher 123 with a Mamiya 500 mm *f*/4.0 lens (The Charles Hulcher Co. Inc., Hampton, VA 23661). Image field of view (FOV) was 12 by 12 m. In 2003, we acquired 2.1-mm GSD imagery using a Canon 1Ds 11 megapixel (MP) digital single lens reflex (dSLR) camera (Canon U.S.A. Inc., Lake Success, NY 11042) with a 420-mm, *f*/2.8, image-stabilized lens configuration at 100 m AGL, yielding a FOV of 5.7 by 8.5 m. In 2008, we acquired imagery from 100 m AGL at multiple resolutions using a three-camera system consisting of the Canon 1Ds with 50-mm *f*/2.0 lens (17.6 mm GSD, 47.6 by 71.6 m FOV), a Canon 1Ds MkII 16-MP dSLR with 100-mm *f*/2.0 lens (7.2 mm GSD, 24 by 36 m FOV), and a Canon 1Ds MkII with 840-mm *f*/5.6 lens (0.86 mm GSD, 2.9 by 4.3 m FOV).

Ground Imagery. We acquired ground imagery in 2002, 2003, and 2008 at VLSA image centerpoints, located with a Garmin eTrex Venture GPS unit (Garmin International, Inc., Olathe, KS 66062). In 2002 and 2003, we used an Olympus E20, 5-MP dSLR camera[4] mounted on an aluminum frame with a 1-m^2 base that positioned the camera for 1-mm GSD nadir images (Booth et al. 2004).

Table 1. Site characteristics and mean canopy cover (%) for five sample areas within the Red Canyon study site calculated from ground-based imagery only. Mean elevation is given for each sample area.

Area	Mean elevation	Mean slope	Year sampled	Downy brome	Perennial grass	Forbs	Bare soil	Shrub
	m	%						
East Burn	1,986	16	2002 (*n* = 14)	3.5 b	12 a	11.36 a	30.64 a	2 a
			2008 (n = 18)	13.35 a	10.49 a	5.14 a	8.73 b	0.45 a
South Burn	2,109	16	2002 (*n* = 20)	0.04 b	12.9 a	12.93 a	29.07 a	2.19 a
			2008 (*n* = 20)	5.18 a	20.59 a	18.56 a	13.14 b	0.84 a
Young Mountain	2,382	23	2002 (*n* = 18)	0 b	11.46 a	16.25 a	28.5 b	2.85 a
			2003 (*n* = 19)	0 b	12.53 a	9.65 ab	45.86 a	2.05 a
			2008 (*n* = 19)	5.29 a	8.52 a	8.52 b	10.56 c	0.26 a
Pass Creek	2,192	21	2003 (*n* = 39)	0 b	11.85 b	15.37 a	55.23 a	0.01 b
			2008 (*n* = 53)	6.87 a	22.49 a	16.47 a	8.89 b	0.58 a
Limestone Mountain	2,670	24	2002 (*n* = 16)	0.03 a	4.88 b	22.96 a	10.04 a	0.37 a
			2008 (*n* = 20)	0 a	20.41 a	14.05 a	6.75 a	4.04 a

[a] Cover values with different lowercase letters differ ($P < 0.05$, corrected with Bonferroni adjustment) among years within a sample area.

Images were cropped to the inner size of the 1-m^2 camera frame base prior to analysis. In 2008, we used an Olympus E510 10-MP dSLR camera (Olympus America Inc., Center Valley, PA 18034) mounted on the aluminum camera stand (< 1mm GSD, 1 by 1 m FOV after cropping).

Image Analysis. We measured percentage of canopy cover from all image sets using 100 sample pixels per image in SamplePoint, a software tool designed for manual cover measurements from digital images (Booth et al. 2006). We classified each pixel into one of the following 10 classes: downy brome, other grass, forb, shrub, litter, bare soil, rock, cactus, shadow, and unknown. Vegetation canopy-cover data were compared among methods (aerial vs. ground) using two-group *t* tests for each cover category. Vegetation canopy-cover change by year was tested for each sampling area with a one-way analysis of variance. Canopy cover data were arcsine transformed to correct for nonnormal distribution. To assess multivariate patterns in vegetation cover (community level), we used principal components analysis (PCA) for each sample area by year. Sample areas were grouped according to similarity in fire history. We used SAS v9.2 (SAS Institute, Carey, NC) for PCA and mean comparisons. Mean comparisons were adjusted using the Bonferroni correction (Dunn's *t* test) to account for type I error among multiple pairwise comparisons. Frequency of occurrence was calculated as the proportion (%) of images for a sample area containing at least 1% cover of each vegetation category. Frequency of downy brome was calculated using individual images as plot observations.

Climate Data. Temperature data from Lander Hunt Field (LHF), located approximately 22 km [13.7 mi] north of the study site at 42°49′03″N, 108°43′37″W, and 1,702 m elevation (NCDC 2011), allowed us to consider a 60-yr trend (1948 to 2008). The long-term mean annual temperature, and mean temperatures for spring (March, April, May) and fall (October, November, December) months, along with their standard deviations (SD) were computed and plotted with a least-squares regression line and a non-zero slope test using Prism 5.0 (GraphPad Software, La Jolla, CA). Daily precipitation data were gathered from the South Pass Snotel weather station (no. 775), located 15 km from the center of the study at equivalent elevation, for the period 1997 to 2008 (NRCS 2011).

Results and Discussion

Aerial vs. Ground Imagery. We found no differences between aerial- and ground-measured canopy cover for 2003 or 2008 sampling events ($P > 0.05$), which implies that comparable canopy measurements can be made from either ground or aerial images having the same resolution. The 2002 aerial imagery lacked sufficient resolution to adequately characterize vegetative cover. The consistent quality and ability to detect vegetative cover from the more recent, higher-quality images of 2003, and especially 2008, confirm that VLSA is a suitable substitute for ground-based imagery for this type of monitoring (Booth and Cox 2008).

Aerial imagery for each year was acquired in 4 h (including takeoff, ferry, and landing time), whereas roughly 80 h were used acquiring ground-based imagery for the same number of images over the same sampling area. This difference in time investment suggests VLSA imagery is an efficient option for quantitatively documenting vegetation cover in remote areas with limited vehicular access.

All sample locations were not represented in each sampling year (2002, 2003, and 2008) for each method

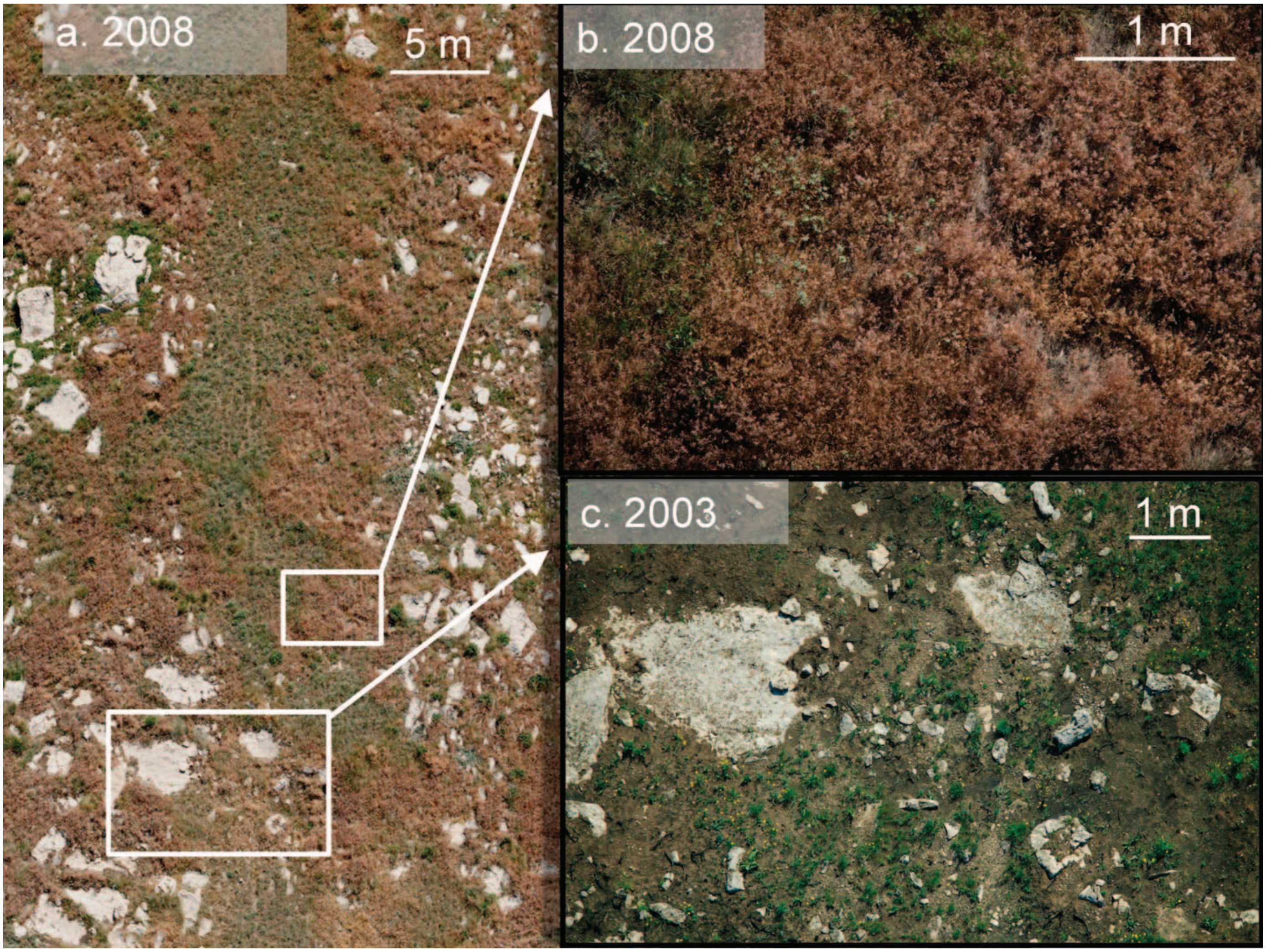

Figure 3. (a) A 17.6-mm ground sample distance (GSD) image from 2008, (b) 0.86-mm GSD image from 2008, and (c) 2.1-mm GSD image from 2003 showing overlap of aerial imagery from 2003 and 2008 at the Pass Creek no. 15 sample location. White boxes in image (a) denote locations where images (b) and (c) occur on the landscape. The rocks in the 2003 image (c) are easily recognized in the 2008 image (a). The slight lack of spatial accuracy between image (b) and image (c) may be because of GPS inaccuracy or slight tilt of the aircraft at the time of shutter release. Note that the wider field of view in image (a) shows the broad extent of downy brome at the sampling location.

of image acquisition (aerial vs. ground). Because high-quality ground images were captured in all three sampling years, but VLSA imagery from 2002 was from film, and of lesser quality than that from 2003 and 2008, we used ground imagery for statistical analyses spanning all three sampling years, but note that where ground images are unavailable, VLSA imagery offers the same analysis potential. VLSA imagery using multiple cameras simultaneously also provides various scales at which patchiness of vegetation can be observed (Figure 3).

Vegetation Cover. All sampled areas exhibit bare soil naturally as a characteristic of the semiarid high-elevation plant communities in which they occur, irrespective of fire history. When all areas across the study site were pooled, frequency of downy brome occurrence increased from 8% in 2002 and 2003 to 44% in 2008, and downy brome canopy cover increased from $< 1\%$ in 2002/2003 to 6.1% in 2008. First-sampled vegetation data within the South Burn and Pass Creek areas were 2 and 1 yr postfire, respectively. Mean downy brome cover at this time for these areas was 0 to 0.4%, but bare soil ranged from 29% to over 55% (Table 1). The East Burn area last burned in 2000, so vegetation data were collected 2 and 8 yr postfire. From the second to the eighth year postfire, mean downy brome cover increased from 3.5% to over 13% across the

East Burn area (Table 1), with some individual sampling locations reaching very high downy brome canopy cover (Figures 3a and 3b).

We used PCAs to explore multivariate (community-level) relationships in vegetation cover. Although because of high variability among sampling sites vegetation cover did not significantly differ in multivariate space among years, PCA results reflect vegetation patterns of the invasion process described in the univariate responses above. The first two components of the PCA for the Pass Creek, Young Mountain, and South areas accounted for 45% of the variation in the data (Figure 4a). The first component had high loadings for perennial grass (0.634) and litter (0.511), and a moderate negative loading for bare soil (−0.432). Increasing values of the first component indicate higher cover of litter and perennial grass, whereas decreasing values are correlated to increasing bare ground. The second component was largely driven by a strong negative loading for downy brome (−0.755) and a high loading for bare soil (0.618). A shift toward negative numbers along this axis indicates increased downy brome cover and decreased bare ground. The plot of the first two components (Figure 4a) reflects a shift from a plant community with much bare ground in 2002 to 2003 and a subsequent increase in downy brome in 2008. Forest Service monitoring records indicate a very small proportion of downy brome in the Young Mountain and Pass Creek areas prior to the 2002 fire (M. Buzalsky, personal communication).

The first two components of the PCA for the East sampling area accounted for 51% of the variation in cover data (Figure 4b). The first component had moderate loadings for forbs (0.520), bare soil (0.510) and a moderate negative loading for downy brome (−0.431), whereas the second component included a moderate negative loading for downy brome (−0.513), a moderate positive loading for shrubs (0.463), and a strong positive loading for litter (0.600). The component plot (Figure 4b) indicates relatively little cumulative change in canopy cover for the east site from 2002 to 2008. The increase in downy brome cover seen in the univariate analysis (Table 1) may be reflected by the slight negative shift on both axes for the 2008 data. The East sampling area burned both in 1999 and 2000, so there may have been sufficient time to accumulate downy brome litter and cover prior to the initial sampling event in 2002. This would be consistent with the pattern observed in the Pass Creek fire data.

The first two components of the PCA for the Limestone Mountain sampling area accounted for 53% of the variation in the canopy cover data (Figure 4c). The first component had a moderate loading for rock (0.566) and moderate negative loadings for forbs (−0.484) and litter (−0.487), and the second component had positive loadings for downy brome (0.406) and soil (0.619) and negative loading for shrub (−0.583). The component plot from the Limestone area (Figure 4c) indicates relatively little change in vegetation cover from 2002 to 2008. Several outlier points from 2002 influence the data toward the positive end of the first component, largely because of high exposed rock in the images. Even though part of the Limestone Mountain area was intentionally burned in 2000, downy brome does not seem to influence the vegetation dynamics

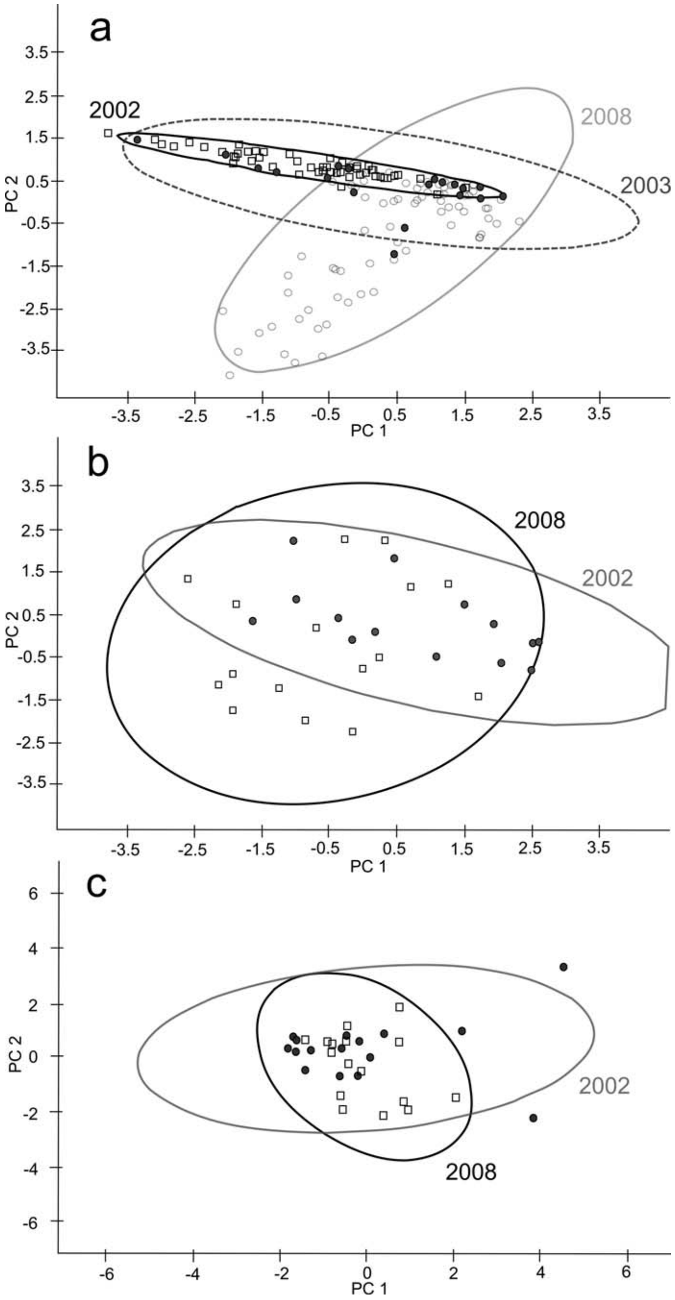

Figure 4. Plots of first and second principal components generated from principal component analyses of canopy cover data for (a) Pass Creek, Young Mountain, and South; (b) East; and (c) Limestone Mountain. sampling areas. Shades indicate sampling year and ellipses represent 95% confidence intervals.

in this area. In fact, perennial grasses significantly increased during the time of observation. Limestone Mountain was the highest-elevation area (mean = 2,670 m) with the most limited fire history during the period of observation, and had a mean bare soil less than 10% (Table 1). The elevation of the Limestone Mountain area may have contributed to a more complete coverage of vegetation from higher precipitation availability.

A relatively clear pattern is apparent from the vegetation data: downy brome is not abundant immediately postfire, but increases as it invades bare soil and replaces forbs and sometimes perennial grasses (see Figure 3 for visual comparison). This pattern of postfire vegetation dynamics was previously documented for sagebrush rangelands in the central Great Basin, where downy brome cover increased from 2% 1 yr postfire to 14% 3 yr postfire (Young and Evans 1978). Elevation in the Great Basin study ranged from 1,500 to 1,800 m with precipitation ranging from 20 to 25 cm (Young and Evans 1978), whereas the present study occurred at elevations ranging from 1,900 to 2,700 m in a precipitation zone of 25 to 35 cm. Downy brome frequency increased by 30 to 50% and cover increased from < 1% to 3.6% at a high elevation in Rocky Mountain National Park over a slightly longer period of observation (Bromberg et al. 2011), in the absence of fire. The similar observations between these studies and the present study suggest the potential for downy brome to become a significant component of rangeland plant communities at higher elevations.

The increased frequency of downy brome occurrence across the landscape may reflect prefire distribution that was not detectable immediately postfire, or it may indicate disturbance-facilitated recruitment into new locations. We are unable to ascertain the mechanism of increased frequency within the scope of this study. However, the results strongly suggest that postfire weed management planning may be misinformed if recommendations are made solely on observable vegetation in the first few years following a wildfire. Incorporation of prefire downy brome distribution data, when available, into postfire reclamation efforts may increase the probability of success.

Climate Data. Sixty years of observations at LHF record a warming trend in annual mean temperature (P = 0.0176) that is consistent with other reports of mountain-region warming trends (Nayak et al. 2010; Parolo and Rossi 2008; Pauchard et al. 2009; Pepin and Lundquist 2008). We also found a significant spring warming trend (P = 0.0003), but the slope of a fall cooling trend was not different from zero (P = 0.32). March had the greatest monthly warming trend (Figure 5).

Precipitation difference among years when vegetation cover was assessed may also have played a role in the observed increase in downy brome cover. Total precipitation in 2002 was lower than in 2008, with winter precipitation being much lower than both 2008 and mean precipitation of the two 6-yr periods leading up to vegetation sampling (Figure 2). Downy brome production is highly variable among years and may be driven by annual precipitation patterns.

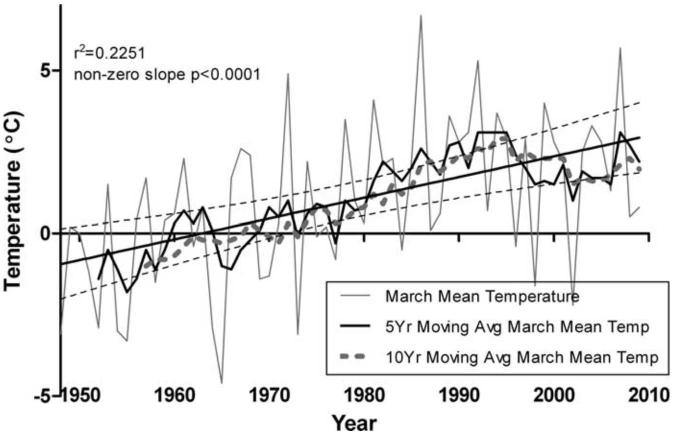

Figure 5. March mean temperature at Lander Hunt Field, WY, from 1948 to 2009.

Higher growing-season temperatures overall may lengthen the period of high moisture stress in late summer, negatively affecting the native plant assemblage at precisely the time when abundant soil moisture would serve to increase native plant seed production and rhizomatous expansion. Vegetation response to warming trends is likely species-specific and situation-dependent (Harte and Shaw 1995; Sternberg et al. 1999), making generalized predictions difficult. Reduced native plant cover and vigor may, over time, reduce competitive suppression of downy brome but hot dry conditions in late summer should not negatively affect downy brome because it grows, sets seed, and senesces early in the season. Downy brome ascendance is likely occurring at higher elevations not only because of the favorable conditions created by earlier spring snowmelt and warmer minimum temperatures, but potentially because of reduced native plant growth under the resulting extended dry season climate. Elucidating mechanisms for the patterns observed here need further experimental research. We cannot definitively state that temperature or precipitation changes, separately or together, contributed to the postfire expansion of downy brome, but the observed, and widely reported, warming trend is biologically consistent with germination and growth requirements of downy brome and may lead to a competitive advantage over native plants, especially when associated with disturbance such as wildfire.

Application. These results indicate the ability of downy brome to invade high-elevation rangelands in Wyoming following wildfire. Prescribed fire is a common tool used for vegetation management in similar plant communities. Mid- to high-elevation rangeland communities slated for prescribed fires should be assessed for presence of downy brome and a postfire annual brome management plan should be developed. Image-based monitoring is an effective and efficient tool for use in such assessment projects, but vegetation characteristics immediately postfire may not accurately depict potential distribution of downy brome. Many land managers may not have the resources (including time) to conduct thorough surveys (Bromberg et al. 2011), but image-based monitoring may present an effective option when time is limited. Wildfire rehabilitation efforts should consider the potential effects of downy brome invasion, even at higher elevations up to 2,500 m. Elevation limits of concern may increase over the coming century with further predicted mean air temperature increases across western North America.

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Literature Cited

Aguirre, L. and D. A. Johnson. 1991. Influence of temperature and cheatgrass competition on seedling development of two bunchgrasses. J. Range Manag. 44:347–354.

Beniston, M., H. F. Diaz, and R. S. Bradley. 1997. Climatic change at high elevation sites: an overview. Climatic Change 36:233–251.

Booth, D. T. and S. E. Cox. 2008. Image-based monitoring to measure ecological change. Front. Ecol. Environ. 6:185–190.

Booth, D. T., S. E. Cox, and R. D. Berryman. 2006. Point sampling digital imagery using 'SamplePoint'. Environ. Monit. Assess. 123: 97–108.

Booth, D. T., S. E. Cox, M. Louhaichi, and D. E. Johnson. 2004. Lightweight camera stand for close-to-earth remote sensing. J. Range Manag. 57:675–678.

Bradley, B. A. 2009. Regional analysis of the impacts of climate change on cheatgrass invasion shows potential risk and opportunity. Glob. Change Biol. 15:196–208.

Bradley, B. A. and J. F. Mustard. 2006. Characterizing the landscape dynamics of an invasive plant and risk of invasion using remote sensing. Ecol. Appl. 16:1132–1147.

Bromberg, J. E., S. Kumar, C. S. Brown, and T. J. Stohlgren. 2011. Distributional changes and range predictions of downy brome (*Bromus tectorum*) in Rocky Mountain National Park. Invasive Plant Sci. Manage. 4:173–182.

Brown, C. S., V. J. Anderson, V. P. Claassen, M. E. Stannard, and L. M. Wilson. 2009. Restoration ecology and invasive plants in the semiarid west. Invasive Plant Sci. Manag. 1:399–413.

Brown, C. S. and H. I. Rowe. 2004. The unwelcome arrival of *Bromus tectorum* to high elevations. Pages 40–51 *in* W. R. Keammerer and J. Todd, eds. Proceedings of the High Altitude Revegetation Workshop No. 16. Fort Collins, CO: Colorado Water Resources Research Institute Information Series No. 99.

Brown, R. D. 2000. Northern Hemisphere snow cover variability and change, 1915–97. J. Climate 13:2339–2355.

Brown, R. D. and P. W. Mote. 2009. The response of Northern Hemisphere snow cover to a changing climate. J. Climate 22: 2124–2145.

Buman, R. A. and R. H. Abernethy. Temperature requirements for mountain rye, hycrest crested wheatgrass, and downy brome germination. J. Range Manage., 41:35–39.

D'Antonio, C. M. and P. M. Vitousek. 1992. Biological invasions by exotic grasses, the grass/fire cycle, and global change. Ann. Rev. Ecol. Sys. 23:63–87.

Day, C. A. 2009. Modeling impacts of climate change on snowmelt runoff generation and streamflow across western US mountain basins: a review of techniques and applications for water resource management. Progress. Phys. Geog. 33:614–633.

Duncan, C. A., J. J. Jachetta, M. L. Brown, V. F. Carrithers, J. K. Clark, J. M. DiTomaso, R. G. Lym, K. C. McDaniel, M. J. Renz, and P. M. Rice. 2005. Assessing the economic, environmental, and societal losses from invasive plants on rangeland and wildlands. Weed Technol. 18:1411–1416.

[FAA] Federal Aviation Administration. 2007 (updated March 31, 2009). Section 6. Light-sport category aircraft airworthiness certifications. Pages 112–125 *in* Airworthiness certification of aircraft and related products. Order 8130.2F. http://www.faa.gov/aircraft/gen_av/light_sport/. Accessed April 9, 2009.

Ganskopp, D. F. and T. E. Bedell. 1979. Cheatgrass and its relationship to climate: a review. Corvallis, OR: Oregon State University Agricultural Experiment Station Special Report 562. 12 p.

Gerlach, J. D., P. E. Moore, B. Johnson, D. G. Roy, P. Whitmash, D. M. Lubin, D. M. Graber, S. Haultain, A. Pfaff, and J. E. Keeley. 2003. Alien plant species threat assessment and management prioritization for Sequoia–Kings Canyon and Yosemite National Parks. Carson City, NV: U.S. Geological Survey Open-File Report 02-170. 149 p.

Harte, J. and R. Shaw. 1995. Shifting dominance within a montane vegetation community: results of a climate-warming experiment. Science 267:876–880.

Hull, A. C. and W. T. Hansen. 1974. Delayed germination of cheatgrasss seed. J. Range Manag. 27:366–368.

Keeley, J. E. and T. W. McGinnis. 2007. Impact of prescribed fire and other factors on cheatgrass persistence in a Sierra Nevada ponderosa pine forest. Int. J. Wildland Fire 16:96–106.

Kindschy, R. R. 1994. Pristine vegetation of the Jordan Crater kipukas: 1978–91. Pages 85–88 *in* S. B. Monsen, and S. G. Kitchen, comps. 1994. Proceedings—Ecology and Management of Annual Rangelands. Ogden, UT: USDA, Forest Service, Intermountain Research Station General Technical Report INT-GTR-313.

Link, S. O., C. W. Keeler, R. W. Hill, and E. Hagen. 2006. *Bromus tectorum* cover mapping and fire risk. Int. J. Wildland Fire 15: 113–119.

Mack, R. N. 1981. Invasion of *Bromus tectorum* L. into western North America: an ecological chronicle. Agro-Ecosystems 7:145–165.

Maher, A. 2007. The Economic Impacts of Sagebrush Steppe Wildfires on an Eastern Oregon Ranch. M.S. thesis. Corvallis OR: Oregon State University. 157 p.

Martens, E., D. Palmquist, J. A. Young. 1994. Temperature profiles for germination of cheatgrass versus native perennial bunchgrasses.

Pages 238–243 *in* S. B. Monsen, and S. G. Kitchen, comps. Proceedings—Ecology and Management of Annual Rangelands. Ogden, UT: USDA Forest Service Intermountain Research Station General Technical Report INTGTR-313.

Nayak, A., D. Marks, D. G. Chandler, and M. Seyfried. 2010. Long-term snow, climate, and streamflow trends at the Reynolds Creek Experimental Watershed, Owyhee Mountains, Idaho, United States. Water Resour. Res. DOI:10.1029/2008WR007525

[NCDC] National Climatic Data Center. 2011. NOAA Satellite and Information Service. http://www.ncdc.noaa.gov/oa/ncdc.html. Accessed: September 13, 2011.

[NRCS] Natural Resources Conservation Service. 2011. National Water and Climate Center, South Pass Snotel Site. http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=775&state=wy Accessed: December 22, 2011.

Parolo, G. and G. Rossi. 2008. Upward migration of vascular plants following a climate warning trend in the Alps. Basic Appl. Ecol. 9: 100–107.

Pauchard, A., C. Kueffer, H. Dietz, C. C. Daehler, J. Alexander, P. J. Edwards, J. R. Arévalo, L. Cavieres, A. Guisan, S. Haider, G. Jakobs, K. McDougall, C. I. Millar, B. J. Naylor, C. G. Parks, L. J. Rew, and T. Seipel. 2009. Ain't no mountain high enough: plant invasions reaching new elevations. Front. Ecol. Environ. 7:479–486.

Pepin, N. C. and J. D. Lundquist. 2008. Temperature trends at high elevations: patterns across the globe. Geophys. Res. Lett. DOI:10.1029/2008GL034026

Smith, M. A. and S. F. Enloe. 2006. Cheatgrass Ecology and Management in Wyoming. Laramie WY: University of Wyoming Cooperative Extension Bulletin MP-111.08. 2 p.

Sternberg, M., V. K. Brown, G. J. Masters, and I. P. Clarke. 1999. Plant community dynamics in a calcareous grassland under climate change manipulations. Plant Ecol. 143:29–37.

Stewart, I. R., D. R. Cayan, and M. D. Dettinger. 2004. Changes toward earlier streamflow timing across western North America. J. Climate. 18:1136–1154.

Tausch, R. J., T. J. Svejcar, J. W. Burkhardt. 1994. Patterns of annual grass dominance on Anaho Islands: implications for Great Basin vegetation management. Pages 120–125 *in* S. B. Monsen, and S. G. Kitchen, comps. 1994. Proceedings—Ecology and Management of Annual Rangelands. Ogden, UT: USDA, Forest Service, Intermountain Research Station General Technical Report INT-GTR-313.

Whisenant, S. G. 1990. Changing fire frequencies on Idaho's Snake River plains: ecological and management implications. Pages 4–10 *in* E. D. McArthur, E. M. Romney, S. D. Smith, and P. T. Tueller, eds. Proceedings of a symposium on cheatgrass invasion, shrub-dieoff, and other aspects of shrub biology and management. Ogden, UT: USDA, Forest Service, Intermountain Research Station General Technical ReportINT-GTR-276.

Wilson, A. M., D. E. Wondercheck, and C. J. Goebel. 1974. Responses of range grass seeds to winter environments. J. Range Manag. 27: 120–122.

Wyoming Pest Detection Program. 2010. Downy brome estimated acres in Wyoming. http://www.uwyo.edu/capswebsupport/Weeds/2010_WEED_MAPS/DOBR_ACRES_10.pdf. Accessed: August 25, 2011.

Young, J. A. and C. D. Clements. 2007. Cheatgrass and grazing rangelands. Rangelands 29:15–20.

Young, J. A. and R. A. Evans. 1978. Population dynamics after wildfires in sagebrush grasslands. J. Range Manag. 31:283–289.

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