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Original Research

Downy Brome Control and Impacts on Perennial Grass Abundance: A Systematic Review Spanning 64 Years☆

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A B S T R A C T

Given the high cost of restoration and the underlying assumption that reducing annual grass abundance is a necessary precursor to rangeland restoration in the Intermountain West, United States, we sought to identify limitations and strengths of annual grass control methods and refine future management strategies. We systematically reviewed all published journal articles spanning a 64-yr period (1948 − 2012; $n = 119$) reporting data on research efforts to either directly or indirectly reduce the abundance of the most common invasive annual grass, downy brome (*Bromus tectorum* L.). The seven most common control methods studied were herbicide, burning, revegetation, woody removal, defoliation or grazing, soil disturbance, and soil amendment. In addition, the majority of control methods were 1) applied at scales of 10 − 100 m^2, 2) sampled within small plots (i.e., 0.1 − 1.0 m^2), 3) implemented only once, and 4) monitored at time scales that rarely exceeded 5 yr. We also performed summary analyses to assess how these control methods affect downy brome and perennial grass abundance (i.e., cover, density, biomass). We found conflicting evidence regarding the assumption that reducing downy brome abundance is necessary to enhance the growth and establishment of perennial grasses. All methods, with the exception of woody plant removal, significantly reduced downy brome in the short term, but downy brome abundance generally increased over time and only herbicide and revegetation remained reduced in the long term. Only burning, herbicide, and soil disturbance led to long-term increases in perennial grass abundance. We suggest that future research should prioritize a broader array of ecological processes to improve control efficacy and promote the reestablishment of desirable rangeland plant communities.

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Introduction

Degradation of dryland plant communities by exotic annual grasses is now recognized as a major driver of global environmental change (Ravi et al. 2009). Annual grass invasion transforms perennial grasslands and desert shrublands, resulting in drastic changes to perennial grass abundance, disturbance regimes, and ecological processes (Seastedt and Pysek 2011). Perhaps the most striking example is illustrated by shrubland and steppe ecosystems of western North America, where downy brome (*Bromus tectorum* L.) is spreading at an alarming rate (Duncan et al. 2004) and is the dominant vegetation on > 2 million ha (Bradley and Mustard 2005). Its spread is a consequence of many interacting factors (Chambers et al. 2014a; Reisner et al. 2013), and when environmental conditions are altered to match predicted climate scenarios (i.e., warming; Bradley 2009), downy brome growth, reproductive output, survival, and phenology shift to favor invasion (Campagnoni and Adler 2014; Zelikova et al. 2013). Consequently, it is spreading to regions where it has not been abundant in the past, including the central and northern Rocky Mountains, southwestern forests, and the northern Great Plains (Bromberg et al. 2011; Douglas et al. 1990; Fowler et al. 2008; Mealor et al. 2012; Pawlak et al. 2015). This trend suggests that control and restoration strategies are keeping pace with neither downy brome rate of spread nor our breadth of ecological understanding of the causes of downy brome invasion and the conditions required to initiate ecosystem recovery (Chambers et al. 2014a; Reisner et al. 2013).

Our understanding of the causes of downy brome invasion rests on > 60 yr of research that reveals a dynamic interaction between disturbance and adaptive traits of the annual grass growth form. As summarized by Mack (1981), downy brome arrived to a region with inferior native plant competitors and to ecosystems that had undergone

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significant modification. In particular, disturbances during settlement in the mid-19th century in the form of clearing land for crops, unrestrained burning, and unregulated livestock grazing (Daubenmire 1940; Hull and Pechanec 1947; Morris et al. 2011; Pickford 1932) created ample opportunities for downy brome to invade where native herbaceous vegetation and biological soil crusts had been removed or severely impaired (Klemmedson and Smith 1964; Mack 1981; Turner 1971). Its long-term persistence and continued spread suggest that it has breached most barriers to invasion during its residency in western North America (Blackburn et al. 2011; Hastings et al. 2007; Hulme 2006).

Because downy brome invasion is associated with displaced native species (Arkle et al. 2014), altered fire regimes, and modified hydrological and soil properties (Blank and Morgan 2013; Davies et al. 2011; Wilcox et al. 2012), impacted ecosystems may not recover by simply removing the invasive grass. Removal may improve ecosystem functioning and the provisioning of services for less-impacted, low-level invasions. However, it is generally understood that highly altered rangeland sites with compromised ecosystem attributes (e.g., biological soil crusts, perennial grasses, and big sagebrush species [*Artemisia tridentata* Nutt.]) (Chambers et al. 2014a; Peterson 2013) can potentially remain in an alternative vegetation state characterized by poor restoration potential (Sheley and James 2014), frequent fires, and exotic species dominance (Young and Evans 1978; Allen and Knight 1984; Knapp 1992; Prevéy et al. 2010; but see Bagchi et al. 2013). Consequently, control efforts must adequately address underlying conditions that favor downy brome dominance (Reisner et al. 2013; Sheley et al. 2010; Wisdom and Chambers 2009). Because downy brome invasion alters the abundance of perennial grasses and their ability to naturally recover following disturbance (Bagchi et al. 2013; Mata-Gonzalez et al. 2007), the manner in which they respond to control methods is also a critical aspect of rangeland management. For example, moderate levels of perennial grass cover equate to appreciable invasion resistance (Anderson and Inouye 2001; Davies 2011; Davies et al. 2010). Furthermore, increasing perennial grasses is considered necessary to initiate recovery toward a system where no further restoration treatments are necessary (Hirsch-Schantz et al. 2014; Nyamai et al. 2011).

Invasive plant management has been criticized for not considering how various control methods influence ecological processes associated with resistance to invasion and ecosystem resilience following disturbance (Brooks and Chambers 2011; Chambers et al. 2014a). Viewing invasive species removal in isolation can result in unexpected changes to other ecosystem components and unwanted secondary impacts (Zavaleta et al. 2001). It may also hamper the development of restoration goals (Buckley 2008; Firn et al. 2008; Hulme 2006; Tzankova and Concilio 2015). Consequently, there is a need to assess annual grass management in a broader ecosystem context to provide a clearer understanding of the strengths and weaknesses of various control methods (Buckley 2008; D'Antonio et al. 2004; Flory and Clay 2009). Fortunately, given the historical and ecological significance of downy brome invasion in western North America, a large body of research literature exists to systematically assess control methods and their impacts on perennial grass recovery. Such an assessment will improve dialogue among researchers and managers and make research results more instructive to practitioners seeking effective management solutions (Boyd and Svejcar 2009; Hulme 2011).

We systematically reviewed and quantitatively summarized the downy brome control literature that spanned > 60 yr. We sought to examine the relative efficacy of control methods, identify the disparities between past research and future downy brome management needs, and prioritize research topics to meet future management needs. We used published research articles to first define the spatial and temporal scales at which experimental treatments were applied and then contrast the impacts of control methods on downy brome and perennial grasses abundance (i.e., biomass, cover, and density). We asked two questions: 1) Do control methods effectively reduce downy brome abundance? and 2) Do control methods affect perennial grass abundance?

Methods

Literature Database

Research articles were assembled from Web of Knowledge (v. 5.9; Thomson Reuters, New York, NY), which accessed two primary databases: Web of Science (1975 − 2012) and CAB Abstracts (1910 − 2012). Using a *topic* search, we acquired citations for all articles that contained any of the following terms: downy brome, cheatgrass, *Bromus tectorum,* and downy chess. Of these ($n = 494$), we omitted articles that were not published in peer-reviewed journals or that did not include original data with downy brome as a response variable. We restricted our search to these criteria to ensure articles were easily accessible to readers.

Systematic Review

As a subset of the downy brome literature database, we identified articles for a systematic review and quantitative summary that met the following criteria: 1) reported original data from a field setting (i.e., we excluded greenhouse and laboratory experiments), 2) were conducted in a rangeland setting (i.e., excluded agricultural crop studies), 3) contained mean values for downy brome or perennial grasses abundance, and 4) directly compared an untreated control with at least one downy brome reduction treatment ($n = 119$; Appendix S1, available online at [doi:10.1016/j.rama.2016.09.008]). We sought to reveal as much relevant information about this body of research as possible by defining trends in article publication over time, patterns of study location, relative prevalence of control methods, occurrence of integrated/multiple control approaches, and contextual elements of studies including treatment plot size, sampling plot size, control period (e.g., method implementation period), and monitoring period. These metadata were recorded for each article and helped identify seven primary control methods: herbicide; burning (prescribed fire and wildfire); revegetation (seeding of perennial grasses); woody plant removal (long-lived shrubs and woodland tree species); defoliation (mowing, grazing); soil disturbance (tillage, disking, and plowing applied before seeding perennial grasses); and soil amendments (adding labile carbon sources to increase microbial soil biomass and immobilize mineral nitrogen in soils and/or treatments to specifically reduce plant litter on soil surfaces). Although woody plant removal studies did not specifically target downy brome, we included them because treatments inadvertently influence downy brome abundance and were frequently applied with other control methods.

Quantitative Summary Analysis

To analyze how the seven control methods influence downy brome and perennial grass abundance, we calculated effect sizes, which are typically used to quantify the magnitude and direction of a treatment using meta-analysis. However, it was not possible to conduct a formal meta-analysis on our dataset because we could not perform the mandatory steps of weighting estimates of effect size by within-study variance for a large proportion of older studies (Vetter et al. 2013). Consequently, because our desire was to include data from all studies that met our criteria, we conducted a quantitative summary analysis of downy brome and woody plant control measures using effect size estimates that do not rely on within-study variance (Hedges et al. 1999). Recent reviews clearly distinguish between meta-analysis and quantitative summary analysis, and the latter does not strictly adhere to standardized meta-analysis methods (Harrison 2011; Koricheva and Gurevitch 2014; Vetter et al. 2013). Effect sizes were calculated as the natural log response ratio, $\ln (X_E/X_C)$, where X_E = treatment mean and X_C = control mean (Goldberg et al. 1999). We then pooled effect sizes and calculated mean effect sizes and 95% confidence intervals. Although this approach runs the risk of misrepresenting the true mean response of a control