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Managing Medusahead (*Taeniatherum caput-medusae*) on Rangeland: A Meta-Analysis of Control Effects and Assessment of Stakeholder Needs☆

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ABSTRACT

Invasive plant response to control efforts is strongly modified by site-specific factors, treatment timing, and environmental conditions following treatment, making management outcomes challenging to predict. Systematic reviews, which involve quantitative synthesis of data, can address this challenge by identifying general patterns of treatment effects across studies and quantifying the degree to which these effects vary. We conducted a systematic review of medusahead (*Taeniatherum caput-medusae* [L.] Nevski) control treatments that couples a meta-analysis on control data with an assessment of stakeholder needs to identify critical medusahead management knowledge gaps. With the meta-analysis we generated effect size estimates of how combinations of herbicide, burning, seeding, and grazing impacted medusahead on rangeland dominated by either annual or perennial vegetation. All combinations of treatments in both rangeland systems provided significant short-term control of medusahead, although treatment effects were highly transient on perennial rangeland, particularly for seeding treatments. Stakeholders listed grazing as a preferred management tool, and on annual rangeland an almost twofold reduction in medusahead abundance was achieved by timing high stocking rates to match phenological stages when medusahead was most susceptible to defoliation. Insufficient data were available to evaluate effects of grazing on medusahead on perennial rangeland. On the basis of these data and our stakeholder survey, four major information needs emerged, including the need to better understand 1) seedbank response to burning and herbicide treatments, 2) how to optimize grazing animal impacts on medusahead given ranch enterprise constraints, 3) costs and benefits of control and risk of practice failure, and 4) impacts of adaptive management treatments conducted on larger scales and at longer time intervals. Addressing these knowledge gaps should help overcome key ecological and economic barriers inhibiting implementation of medusahead and other invasive plant management programs on rangeland and provide a positive step toward conserving the critical ecosystem services these systems provide.

Introduction

The fundamental goal of rangeland ecology is to develop practical solutions for key rangeland management challenges. Similar to other applied disciplines, however, end users of research (e.g., producers, public land managers, conservation groups) often find it difficult and time intensive to navigate and distill the array of data and results that can inform management decisions (Zavaleta et al., 2008; Aslan et al., 2009; Sheley et al., 2010). As a result, in many situations, management decisions may be based on experience, common practice standards, or advice from other end users (Sutherland et al., 2004), instead of the collective evidence generated by research. The increasingly

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complex nature of rangeland resource management and progressively decreasing time and financial resources available to managers highlight the need to move toward evidence-based management of rangeland resources (Briske, 2011).

Systematic reviews provide a foundation for evidence-based management and are becoming more common in applied ecology fields (Sutherland et al., 2004; Cook et al., 2013). One challenge with systematic reviews, however, centers on a common trade-off between scope and practical utility. Namely, systematic reviews of broad natural resource issues are useful for identifying general principles and trends, but they often do not yield specific information needed by managers (Cook et al., 2013). A recent assessment of systematic reviews found that the utility of reviews for making practical management recommendations increased as geographic scope increased but declined as taxonomic diversity increased (Cook et al., 2013). Thus while the general utility of evidence-based conservation is well established, the scale of reviews must be carefully considered if the efforts are to be most useful to managers.

In addition to establishing a relevant scale, a key driver of systematic review utility is centered on stakeholder input (Fazey et al., 2004; Pullin and Stewart, 2006). Despite the clear value of including stakeholders in the systematic review process, stakeholder input is often overlooked or poorly documented (Cook et al., 2013). In most cases, systematic review findings are not assessed by stakeholders. As a consequence, we often do not know if reviews and associated synthesized research are providing answers that managers most urgently need (Cook et al., 2013). By including stakeholders in the systematic review process, we gain opportunities to identify critical knowledge gaps and direct future research efforts (Sutherland et al., 2006; Robison et al., 2010; Braunisch et al., 2012).

Invasive plant management on rangeland may be particularly well situated to benefit from systematic reviews. In most cases, the majority of ecological impacts resulting from invasive plants are driven by a subset of species, distributed across a large area, thus reaching an appropriate tradeoff between geographic scale and taxonomic diversity. In addition, invasive plant response to control efforts is often heavily modified by site-specific environmental conditions, making it difficult to quantify the magnitude and variation of likely management outcomes from individual studies. A number of valuable general reviews of invasive plant management on rangeland have been conducted and have yielded important general management principles (DiTomaso, 2000; Duncan et al., 2004; Sheley et al., 2011). There are opportunities to extend these efforts using systematic reviews that quantitatively synthesize the literature on management of key invasive plant species to generate a likely distribution of management outcomes.

The objective of this study was to conduct a systematic review of medusahead (*Taeniatherum caput-medusae* [L.] Nevski) control treatments that coupled a meta-analysis on control data with an assessment of stakeholder needs to identify critical knowledge gaps related to medusahead management. We then used these linked efforts to identify critical knowledge gaps and research needs. Medusahead is an annual grass from Eurasia and is one of the most detrimental invasive plant species on rangeland in the western United States. Ecological and economic impacts of this species are far reaching and include decreased forage quality, altered fire regimens, reduced wildlife habitat quality, reduced biodiversity, and changes in soil nutrient and water cycles (D'Antonio and Vitousek, 1992; Kulmatiski et al., 2006; Davies and Svejcar, 2008). Medusahead is able to establish and rapidly spread on rangeland dominated by annual grasses and perennial rangeland dominated by perennial grasses and shrubs. Medusahead currently dominates almost 1 million ha of rangeland in California, Oregon, Nevada, Utah, Idaho, Washington, and portions of Montana (Duncan et al., 2004). Although an array of stakeholders continue to manage rangeland threatened or dominated by medusahead using combinations of herbicide, prescribed fire, grazing, and seeding, most indicators suggest medusahead is spreading largely unchecked (Young, 1992; Davies and Johnson, 2008). Thus there is a clear need to quantitatively assess outcomes of common control efforts and identify the most critical knowledge gaps serving as management barriers.

Several qualitative reviews on the ecology and management of medusahead over the past several decades have been published (Young, 1992; Miller et al., 1999; Nafus and Davies, 2014), but there has been no quantitative synthesis of research on medusahead control strategies or any effort to evaluate the degree to which current research is answering questions most important to managers. Although qualitative reviews on medusahead have provided stakeholders with a solid management foundation, a quantitative synthesis can provide insights that can greatly extend current qualitative understanding, including generation of an unbiased estimate of effect size across treatments and quantification of the degree the effect size may vary as a function of environmental conditions (Gurevitch and Hedges, 1993). This information is key because it provides stakeholders with the understanding of the potential range of outcomes of various management strategies and some assessment of the potential risk of practice failure. In most land management scenarios, the risk of practice failure is at least as important as costs in determining if managers will implement the practice (James et al., 2013).

In this study we use meta-analysis to estimate the distribution in effect size for the most commonly used medusahead management tools including herbicide, burning, grazing, and seeding. We generate these estimates for both rangeland dominated by annual grasses (annual rangeland) and rangeland dominated by perennial plants (perennial rangeland) and then use a broad stakeholder group to evaluate the degree to which research results correspond to management expectation and management information needs. These two efforts are then used to identify critical knowledge gaps and outline key directions for future research.

Methods

Systematic Review and Meta-analysis

Question Formulation, Search Strategy, and Study Quality

Our approach to the systematic review and meta-analysis of research on medusahead control broadly followed the recommendations of Pullin and Stewart (2006). Our question was developed with medusahead as the subject and control treatments to reduce medusahead including herbicide, grazing, burning, herbicide and seeding, and burning and seeding as the interventions. Our measured outcome was change in medusahead cover, biomass, or density. We evaluated how the outcome of different control treatments differed across rangeland dominated by annual grasses (annual rangeland) and rangeland dominated by perennial grasses (perennial rangeland). We also evaluated how these responses varied over time. These elements allowed formulation of the following questions: Do different control treatments have different effects on medusahead abundance? Do effects of a control treatment differ between perennial and annual rangeland? Do impacts of control treatments change through time?

Suitable studies for our review were identified with key words used in our questions. We performed key word searches using ISI Web of Science for studies published between 1960 and 2013, Agricola, Digital Dissertations, and archived databases managed by the University of California. Bibliographies of articles generated in this initial search were identified, and we also acquired articles and data through personal communication. For inclusion in the meta-analysis, studies or data sets needed to demonstrate an appropriate experimental design including replication and appropriate selection of control and treatment experimental units. We considered all possible outcome metrics including medusahead cover, biomass, or density. Quality of all candidate studies was assessed independently by two reviewers. For each study we noted size of experimental unit, maximum duration of observation, and whether or not treatment costs were described.

Data Extraction and Analysis

We found a total of 57 studies, of which 22 met our minimum inclusion criteria for use in our meta-analysis. These studies yielded 184 independent data points (individual studies contribute more than one data point if they used different sites and/or treatments, Table S1, available online at http://dx.doi.org/10.1016/j.rama.2015.03.006). Means, sample sizes, and standard deviations were recorded for both control and experimentally treated plots. Data were collected from published tables, received directly from investigators, or derived from published figures using datathief III (available online at http://datathief.org/).

Key medusahead management treatments evaluated included herbicide, grazing, burning, herbicide + seeding, burning + seeding, and herbicide + burning + seeding. Herbicide treatments included the postemergence herbicide glyphosate ($n = 3$) and a number of pre-emergent herbicides including imazapic ($n = 21$), rimsulfuron ($n = 3$), aminopyralid ($n = 3$), and sulfometuron ($n = 4$). Several herbicides were only used in a single study, including atrazine, bromacil, clopyralid, dalapon, isocil, isopropyl, and picloram, and were therefore not amendable to meta-analysis. An insufficient number of studies using multiple herbicide rates to allow evaluation of herbicide rate on medusahead abundance was available. For studies that included multiple rates we used the highest rate in our analysis.

Grazing treatments included grazing by cattle and sheep ($n = 29$). Because multiple studies tested multiple levels of grazing timing and intensity, we analyzed the average effect size across all grazing treatments. For studies using multiple grazing levels we also reported the average effect size for the treatments that resulted in the largest medusahead control. We chose to report both values because grazing in general is expected to be an important weed control strategy (Sheley et al., 2011), and targeted grazing (adjusting grazing timing and intensity to have maximum impact on a particular plant species or vegetation type) is generally expected to result in additional decreases in invasive plant abundance (Rinella and Hileman, 2009).

Burning included studies that used prescribed or wild fire ($n = 15$). Herbicide + seeding treatments included use of either postemergent or pre-emergent herbicide followed by seeding various combinations of native and introduced plants ($n = 21$). Both the burn + seeding ($n = 7$) and the herbicide + burn + seeding treatments ($n = 4$) used only one seeding rate, so it was not possible to assess effects of seeding rate on medusahead abundance.

In cases where studies recorded medusahead response to a treatment across multiple yr, we analyzed treatment effects 1 yr after treatments were applied and effects 2 or more yr after treatments were applied. We further organized our data by location of experiment, including either rangeland dominated by annual grasses in western California and Oregon foothills and valleys, or perennial rangeland dominated by perennial grasses, forbs, and shrubs in eastern Oregon, eastern California, Nevada, Idaho, and Utah.

We used the log response ratio (ln R) to estimate treatment effects across studies (Hedges et al., 1999) where the effect size estimate ln RR is calculated as $\ln RR = \ln(X^E/X^c)$ where X^E and X^C are means of the experimental and control groups, respectively. The variance of the response ratio is calculated as:

$$V_{\ln\ R} = \left(s^E\right)^2/N^E\left(X^E\right)^2 + \left(s^C\right)^2/N^C\left(X^C\right)^2$$

where s^E and s^C are standard deviations of the experimental and control groups, respectively, and N^E and N^C are sample sizes of the experimental and control groups, respectively. To reduce the bias introduced from differences in sample size among studies, a weighted average (the reciprocal of the sampling variance) was applied to our response ratios to determine a cumulative effect size for our studies. The final log response ratios were normally distributed with Q-Q plots. Because our data were normally distributed, we did not employ resampling techniques. The cumulative effect size was determined significant if the confidence interval (CI) for that effect size did not bracket zero.

Assessment and Synthesis of Stakeholder Needs

In fall 2013, we convened a group of 93 stakeholders for a one-day forum to review current research on medusahead management, review the meta-analysis findings, and assess stakeholder experiences on medusahead management information needs. Stakeholders represented a broad range of groups involved with medusahead management, including ranchers, county, state and federal land managers, and academic researchers, as well as other key groups. This stakeholder group was not a random sample of all potential stakeholders concerned with medusahead management. Thus survey responses and needs assessments cannot necessarily be extended to the entire stakeholder population. Given the breadth of participation in this forum, however, there is a strong likelihood that identified salient research themes and information needs will be highly relevant to a larger stakeholder base.

During the forum, stakeholders were asked to complete a survey that evaluated several key areas of medusahead management, including objectives of medusahead management; willingness to pay for medusahead prevention and control; perceived efficacy of various medusahead control treatments; likelihood of using various medusahead control treatments; perceived barriers to medusahead management; and overall prospects regarding the future of medusahead management. From this survey and the day-long review of current research on medusahead management, we then asked the stakeholder group to distill their experiences and opinions down to what they felt were the most critical knowledge gaps and research needs on medusahead management.

Results

General Study Attributes

Of the studies included in the meta-analysis, average plot size for herbicide, grazing, and burning treatments were 0.01, 0.21, and 0.84 ha, respectively (Table S1). Following treatment, 22% of studies monitored medusahead response for only 1 yr while 63% monitored for 2 or 3 yr. Three studies followed medusahead response to treatment more than 3 yr. None of the studies used in the meta-analysis reported total input costs across all treatments.

Meta-analysis

Averaged across all herbicide types, herbicide application significantly reduced medusahead abundance below that of the untreated control during the first growing season on annual and perennial rangeland (Fig. 1, top panel). Glyphosate produced the largest negative effect on medusahead on annual rangeland while other herbicides had relatively small but significant negative effects on medusahead. Beyond 1 yr following treatment, the negative effect of glyphosate on medusahead on annual rangeland decreased but effect size remained significantly below

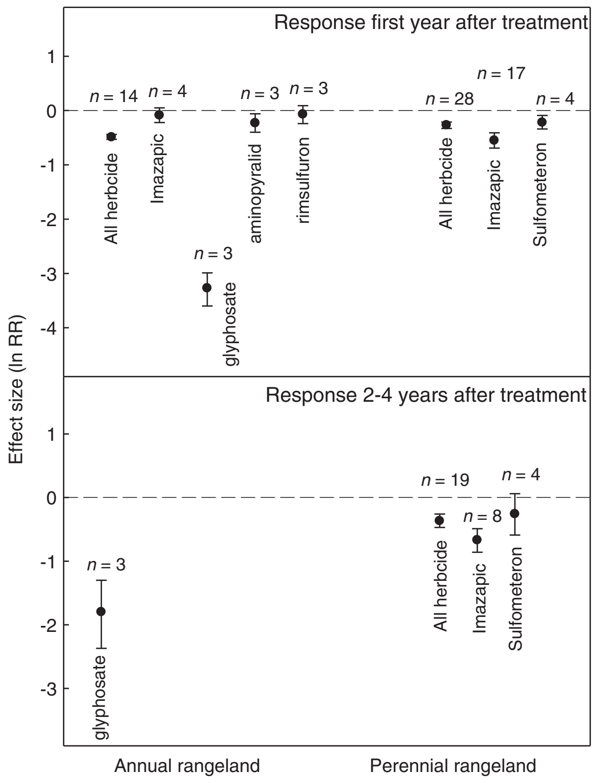

Fig. 1. Average weighted effect size values (solid circles) and 95% confidence intervals (vertical bars) on log response ratios (lnRR) where lnRR = ln (medusahead abundance in plots sprayed with herbicide) – ln (medusahead abundance in untreated plots). Treatments with negative effect sizes and with confidence intervals that do not overlap zero had a significant negative impact on medusahead abundance. The upper panel shows treatment effects during the first growing season following treatment on annual and perennial rangeland. The lower panel shows treatment effects 2 to 4 yr after treatments were applied. Relevant treatment details for each study are listed in Table S1 (available online at http://dx.doi.org/10.1016/j.rama.2015.03.006).

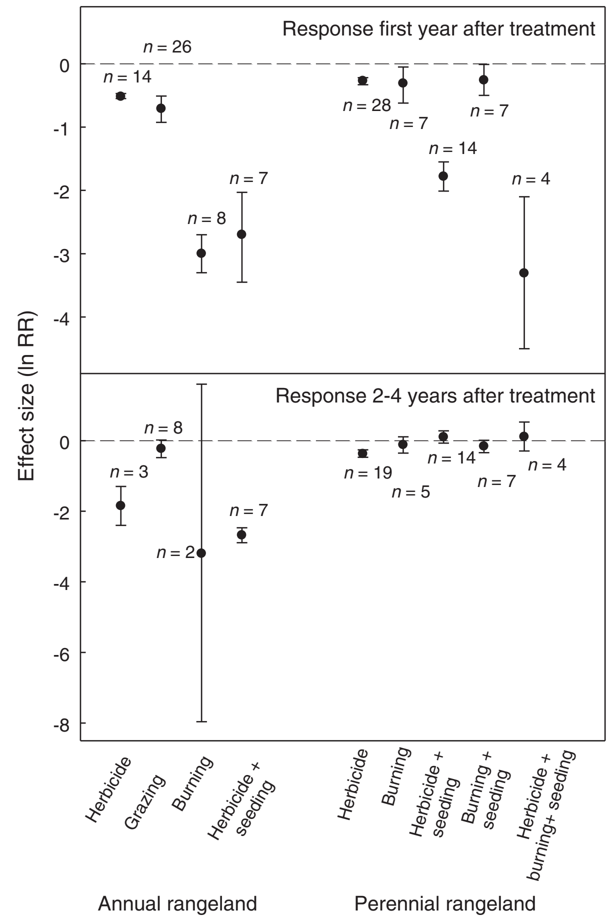

Fig. 2. Average weighted effect size values (solid circles) and 95% confidence intervals (vertical bars) on log response ratios (lnRR) where lnRR = ln (medusahead abundance in treated plots) – ln (medusahead abundance in control plots). Treatments included herbicide, defoliation, burning, and seeding combined with other treatments. Treatments with negative effect sizes and with confidence intervals that do not overlap zero had a significant negative impact on medusahead abundance. The upper panel shows treatment effects during the first growing season following treatment on annual and perennial rangeland. The lower panel shows treatment effects 2 to 4 yr after treatments were applied (depending on study). Relevant treatment details for each study are listed in Table S1 (available online at http://dx.doi.org/10.1016/j.rama.2015.03.006).

zero (Fig. 1, lower panel). Likewise, the various herbicide treatments applied on perennial rangeland reduced medusahead abundance more than the untreated plots following the second or third growing season of the studies.

On annual rangeland, burning and herbicide + seeding showed large negative effects on medusahead abundance in the first growing season following treatment and effect size of these treatments were more negative than herbicide alone (Fig. 2, upper panel). On perennial rangeland, burning and burning + seeding resulted in levels of medusahead abundance that were similar to herbicide alone the first yr following treatment. On perennial rangeland following the first yr of treatment, herbicide + seeding resulted in a larger negative effect on medusahead abundance compared with herbicide alone. Likewise, the first yr following treatment herbicide + burning + seeding resulted in a larger negative effect on medusahead abundance compared with herbicide + seeding or burning + seeding.

On annual rangeland, the negative effects of herbicide and seeding on medusahead abundance persisted beyond 1 yr following treatment (Fig. 2, lower panel). The negative effects of burning on medusahead abundance, however, appeared to be more transient and variable, although the low sample size ($n = 2$) limits inference. On perennial rangeland, the negative effects of herbicide on medusahead abundance persisted beyond 1 yr following treatment while negative effects of burning and combinations of herbicide, burning, and seeding on medusahead abundance disappeared beyond 1 yr following treatment.

Grazing medusahead on annual rangeland resulted in significant reductions in medusahead abundance the first yr following treatment (Fig. 2, upper panel), despite large differences in grazing timing, stocking rate, pasture size, and animal class (Table 1). The negative effect of grazing diminished beyond 1 yr following treatment and was not significantly different from zero, indicating medusahead had reached comparable abundance in grazed versus ungrazed pastures after 2 or more yr following removal of grazing (Fig. 2, lower panel). Data to quantitatively evaluate the effect of grazing timing and intensity on medusahead abundance were insufficient. For studies that evaluated multiple levels of grazing timing and intensity, the maximum average effect size across studies was -1.2 (-2.0 to -0.5) (mean, 95% CI), which was almost double the effect size across all combinations of defoliation treatments (Fig. 2., upper panel). Data for the perennial region to evaluate effects of grazing on medusahead abundance were insufficient, with only one study (Young and Evans, 1971) reporting treatment effects in this category.

Table 1
Description of grazing treatments and corresponding effect sizes for the five studies that tested effects of 29 grazing treatments on medusahead abundance. The average effect size across all treatments is reported in Fig. 2. Effect size (ln RR) ln (medusahead abundance in plots sprayed with herbicide) – ln (medusahead abundance in untreated plots). Treatments with negative effect sizes and with confidence intervals that do not overlap zero had a significant negative impact on medusahead abundance.

Study	Animal class	Days grazed	Timing of defoliation	Stocking rate (AUM ha^{-1})	Pasture size (ha)	Sample size	Effect size (ln RR)	Effect size variation
(DiTomaso et al., 2008)	Sheep	14	Oct 30 to Nov 3, Apr 22 to 30	6.7	0.01	8	-2.40	0.29
	Sheep	22	Oct 30 to Nov 3, Mar 14 to 21 & Apr 22 to 30	6.7	0.01	8	-2.11	0.30
	Sheep	13	Oct 30 to Nov 3, Mar 14 to 21	3.3	0.01	8	0.01	0.16
	Sheep	5	Oct 30 to Nov 3	3.3	0.01	8	0.02	0.24
(Cherr, 2009)	Sheep	20	Apr 7 to Apr 26	3.1	0.2	6	-1.82	0.07
(Reiner and Craig, 2011)	Cattle	180	Not reported	0.84	3532	5	-0.49	0.39
(Turner, 1969)	Sheep	36	Late May	13	0.20	3	0.17	0.40
	Sheep	27	Mid Apr & Late May	10	0.20	3	0.27	0.25
	Sheep	14	Mid Apr	5	0.20	3	0.48	0.23
(Laca, 2010)	Cattle	11	Apr 21 to May 5	1.69	1.53	5	-1.18	0.28
	Cattle	21	Apr 21 to May 12	1.87	1.44	5	-0.66	0.12
	Cattle	14	Apr 21 to May 5	2.22	1.48	5	-0.65	0.81
	Cattle	21	Apr 21 to May 5	1.92	0.70	5	-0.60	0.60
	Cattle	21	Apr 21 to May 12	1.78	1.51	5	-0.59	0.28
	Cattle	21	Apr 21 to May 12	1.97	0.76	5	-0.55	0.25
	Cattle	14	Apr 21 to May 5	1.95	1.38	5	-0.42	0.24
	Cattle	21	Apr 21 to May 12	1.8	0.75	5	-0.32	0.22
	Cattle	14	Apr 21 to May 5	1.97	0.76	5	-0.23	0.09
	Cattle	21	Apr 21 to May 12	1.77	0.76	5	-0.04	0.14
	Cattle	14	Apr 21 to May 5	2.27	0.79	5	0.31	0.28
	Cattle	14	Apr 21 to May 5	1.85	1.45	3	-1.36	0.58
	Cattle	21	Apr 21 to May 12	1.84	0.73	3	-1.01	0.49
	Cattle	21	Apr 21 to May 12	3.68	1.47	3	-0.97	0.58
	Cattle	14	Apr 21 to May 5	2.1	0.77	3	-0.64	0.52
	Sheep	25	Apr 23 to May 17	3.55	0.40	5	0.40	0.41
	Sheep	31	Apr 17 to May 17	4.37	0.40	5	-0.89	0.54
	Sheep	31	Apr 17 to May 17	3.65	0.20	5	-0.84	0.52
	Sheep	17	Apr 25 to May 11	8.60	0.20	5	-0.67	0.57
	Sheep	33	Apr 15 to May 17	3.85	0.20	5	-0.27	0.62

Table 2
Stakeholder response (mean and standard deviation) regarding their level of agreement with the following statements based on a 5-point scale (1 strongly disagree, 5 strongly agree).

	Mean (SD)
The reasons I manage medusahead are:	
To improve plant diversity	4.3 (0.8)
To increase forage quality/quantity	3.5 (1.2)
To improve wildlife habitat	3.5 (0.9)
To decrease fuel on rangeland	2.5 (0.9)
Other management reasons	1.7 (1.2)
The barriers to managing medusahead are:	
Treatment cost compared to benefits	3.6 (1.1)
Time to dedicate toward weed management	3.5 (1.2)
Risk of weed control treatments failing	3.3 (1.2)
Lack of information about how to apply treatments	2.9 (1.2)
Government regulations	2.9 (1.1)
Compatibility of weed management with other management objectives	2.9 (1.1)
Tools available for management	2.7 (1.1)
The following tools are effective for managing medusahead	
Prescribed fire	3.6 (1.1)
Targeted grazing	3.6 (1.1)
Herbicide	3.5 (1.1)
Seeding desired plants	3.5 (1.0)
I am likely to use the following tools to manage medusahead	
Targeted grazing	3.2 (1.5)
Seeding desired plants	2.9 (1.3)
Prescribed fire	2.3 (1.4)
Herbicide	2.1 (1.3)
Indicate your level of agreement with the following statements:	
Controlling medusahead is a complex long-term process that does not have a single general management solution	4.5 (0.9)
Controlling medusahead will only be achieved by developing cheap and simple tools that produce predictable results	3.6 (0.8)
Available tools are sufficient to control medusahead	3.0 (1.0)

Stakeholder Experiences and Research Needs

The 93 stakeholders participating in the day-long research review and survey represented an array of groups including producers and agricultural industry (17%), academia (9%), nongovernmental organizations (12%), NRCS (15%), federal research agency (10%), state government agency (15%), county government agency (9%), and consulting/private land managers (13%). When asked about their reasons for managing medusahead, there was substantial variation across this stakeholder group, indicating a wide diversity in management goals (Table 2). Although no single management objective emerged as a unifying goal, improving plant diversity, increasing forage quality/quantity, and improving wildlife habitat emerged as the three highest-ranked goals. Similar to management objectives, there also was a wide range in perceived barriers to managing medusahead with treatment cost relative to benefit, risk of weed control failure, and time needed for weed management listed as the three highest management barriers. When asked about willingness to pay for medusahead prevention and control, our stakeholder group indicated they would be willing to pay $US 25 $\pm$ 27 and $US 42 $\pm$ 37 (mean $\pm$ SD) per hectare per yr over a 5-yr period to prevent and control medusahead, respectively. Stakeholders generally perceived common management tools, including prescribed fire, herbicide, seeding, and targeted grazing, to be equally effective at controlling medusahead but were more likely to use targeted grazing to control medusahead than other control treatments.

When stakeholders were asked to identify major knowledge gaps by comparing their knowledge, beliefs, and experiences managing medusahead with the major body of medusahead control research reported in our systematic review, three themes were identified including the need to 1) better understand benefits of managing medusahead relative to management costs and risks; 2) develop simple decision tools that would allow managers to track and appropriately adjust management through time; and 3) better understand outcomes of management inputs over longer time periods and at larger management scales. When asked about statements that generally reflected their long-term view on the future of managing medusahead, the majority of stakeholders largely viewed medusahead management as a complex, long-term process that did not have a single general management solution and agreed less strongly with the idea that successful medusahead management programs would depend on the development of simple and inexpensive tools yielding predictable management outcomes.

Discussion

Our systematic review pooled multiple decades of research on medusahead control across the western United States and quantified the magnitude and variation in which common control treatments influence medusahead abundance. This synthesis revealed a number of key patterns that refine our current understanding of how common control strategies impact medusahead abundance, which, in turn, provides the foundation for evidence-based medusahead management. In addition, coupling key patterns observed in the systematic review to assessments of stakeholder information needs provides insight into how scientist and managers might hone future cooperative research efforts to address critical knowledge gaps. We explore these linkages under four major themes below.

Use Herbicide and Burning to Control Medusahead

On both perennial and annual rangeland, our meta-analysis found herbicide and burning was initially effective in controlling medusahead abundance. These patterns held despite studies occurring under widely varying sets of environmental conditions that influence treatment outcomes, such as fuel loads and rainfall, as well as the timing, rate, and form of herbicide application (DiTomaso et al., 2006; Kyser et al., 2007). It is widely understood that the negative impacts of herbicide and burning on medusahead will be transient unless there is a sufficient pool of desired species in the seedbank that are able to establish following medusahead control (Seabloom et al., 2003; Sheley et al., 2009; Kyser et al., 2013). We found that seeding following herbicide application on annual rangeland results in larger negative effects on medusahead relative to herbicide alone. This suggests that on annual rangeland the density of desired species in the seedbank limits the degree to which control treatments convert medusahead-dominated rangeland to rangeland dominated by desired species and that practitioners could expect that seeding with desired species following herbicide will significantly reduce medusahead more and for a longer duration than herbicide alone.

Although these benefits of seeding following invasive plant control efforts are intuitive and likely expected by most managers, on perennial rangeland our meta-analysis found that seeding following herbicide and/or burning did not negatively impact medusahead abundance more than the control efforts alone. Moreover, by the second or third yr, treatments involving seeding with combinations of herbicide and burning did not have lower medusahead abundance compared with untreated plots. Collectively, these patterns suggest that on perennial rangeland, augmenting the seedbank with desired species does not translate into establishment of desired species in sufficient densities to significantly reduce medusahead abundance.

The challenges of establishing desired species on rangeland are well described (Pyke, 1990; Chambers, 2000; James et al., 2011), but these results clearly frame needs and opportunities to advance invasive plant management programs on rangeland. The stakeholder group surveyed in this study indicated they were likely to use combinations of herbicide and seeding to control medusahead, and current management policies on public lands suggest seeding will continue to be a key component of restoration and revegetation efforts on public land throughout the western United States (Pellant et al., 2004; Eiswerth et al., 2009). In general, our meta-analysis found that research on medusahead control tended to be largely centered on herbicide efficacy with less than 15% of data included in the meta-analysis examining effects of seeding on medusahead abundance following medusahead control efforts. The need to focus research in this area is further underscored in our stakeholder survey where stakeholders describe how the risk of practice failure influences medusahead management decision making. Seeding is generally recognized as a management practice with one of the highest risks of practice failure and highest costs (Hardegree et al., 2011). Stakeholders in our study described risk of practice failure and high cost as one of the key barriers to implementing and maintaining a medusahead management program. Thus while opportunities to refine herbicide research remain, our meta-analysis and stakeholder responses indicate a clear need for future work to explicitly focus on mechanisms and process driving seedling establishment following control efforts and how this collective understanding can be used to forecast practice outcomes, as well as identify strategies and tools to reduce practice failure.

Defoliation with Domestic Grazing Animals to Control Medusahead

Domestic grazing animals are the most common vegetation management tool on rangeland because of their cost-effectiveness, ability to evenly utilize heterogeneous landscapes, and ability to address other land management objectives (Bernues et al., 2014; Sheley et al., 2014). Not surprisingly, stakeholders surveyed in our study listed grazing animals as one of the most common tools to use for managing medusahead. On annual rangeland, our meta-analysis suggested grazing produces moderate negative effects on medusahead abundance the first yr, and this effect was comparable with the effect size generated from herbicides. Studies that optimized timing and stocking rate to correspond with periods when medusahead was most susceptible to grazing reduced medusahead abundance almost twofold more than the average effect size of all grazing treatments. Our meta-analysis results, therefore, provide quantitative support to the broadly held notion that grazing animals over a range of appropriate grazing regimens provides clear benefits for invasive plant control, and more intensive and precise management of grazing produces additional benefits.

Our meta-analysis showed clear benefits of grazing to control medusahead, yet practical application of targeted grazing at management scales may be more challenging. To negatively impact annual grass seed production, animals need to defoliate growth points at a stage when plants have limited capacity to produce new reproductive tillers (Hempy-Mayer and Pyke, 2008). Medusahead palatability, however, decreases with increasing phenological stage, and livestock progressively show preference for other forage species as the phenological stage of medusahead increases (Lusk et al., 1961; George, 1992). As a consequence of these phenological changes, there may only be a 2-wk window where plants are palatable to livestock but still susceptible to defoliation (Lusk et al., 1961; Young et al., 1970).

The majority of the grazing studies in our meta-analysis attempted to target at least a portion of this time period in which medusahead is susceptible to grazing. On annual rangeland, this occurs between April and May depending on weather and site conditions (McKell et al., 1962; DiTomaso et al., 2008). Targeting high utilization over such a short time interval may be difficult on an operational scale. On annual rangeland, current estimates suggest animal densities must be sufficient to remove 70% of the forage within a 2-week window to significantly impact medusahead abundance (E. A. Laca, 10/9/15, personal communication). For context, assuming 25% spoilage, a 1-ha pasture with a standing crop of 2500 kg $\cdot$ ha^{-1} would require 7.8 animal units (AUs), where one AU is approximately the average forage demand of a cow–calf pair, to provide the necessary density of grazing animals over a 14-d time period to reach target utilization (2 500 kg $\cdot$ ha^{-1} $\times$ 0.70 $\times$ 0.75/[12 kg AU d^{-1}])/14 d $=$ 7.8 AU ha^{-1}). This is equal to 3.6 AU months (AUMs) ha^{-1} over the 14-d period and a stocking rate comparable with the rates used by the studies in our meta-analysis (average 5.6 AUMs ha^{-1}, Table 1). However, over a typical 6- to 7-month grazing season on annual rangeland (late October to late May), stocking rates are often less than 1 AUM ha^{-1} (Reiner and Craig, 2011). While uniformly grazing large pastures would be difficult given the large numbers of animals needed for short periods of time, it may be practical to use temporary fencing to strategically target certain portions of pastures with high medusahead abundance (DiTomaso et al., 2008). Likewise, it may be reasonable to apply other medusahead control treatments to different portions of a pasture that may complement grazing and extend the spatial scale and timing in which medusahead control efforts could be applied. Research on these two types of approaches would be an important step toward increasing the utility and impact of grazing animals on invasive plants like medusahead, especially if these efforts are tied into basic cost/benefit analysis to better understand tradeoffs associated with these strategies and conventional management approaches.

Beyond the need to increase our understanding of how to optimize targeted grazing at an operational scale, two additional key knowledge gaps associated with grazing emerged from our meta-analysis. First, the bulk of the research has focused on short-term effects of intensive grazing on medusahead abundance with only 8 of the 29 grazing treatments following grazing effects beyond 1 yr post grazing. Grazing systems are most often developed as long-term management tools, suggesting it might be useful to extend our understanding of how different long-term grazing management programs, coupled with other rangeland management practices such as water development and livestock supplementation, impact medusahead abundance (George et al., 1989). It may be possible that over longer time intervals and in conjunction with other rangeland management practices, the high medusahead utilization rates (i.e., 70%) currently targeted in intensive grazing management efforts could be reduced, lowering the required number of animals and making these efforts more feasible. Second, with the exception of one study (Young and Evans, 1971), we found no data in the peer-reviewed literature that evaluated how grazing can be used to control medusahead on perennial rangeland. The large differences in life history, productivity, and phenology of desired species between perennial and annual rangeland limit the degree to which grazing research on annual rangeland can inform medusahead control efforts on perennial rangeland. In addition, larger pasture sizes and lower stocking rates on perennial rangeland compared with annual rangeland likely will exacerbate practical constraints associated with targeted grazing, similar to those shown for cheatgrass (Diamond et al., 2009). Thus while annual and perennial rangeland share similar information needs in terms of how grazing systems in conjunction with other rangeland management practices influence medusahead abundance over the long term, managers of perennial rangeland also may benefit with additional information on how livestock select and utilize medusahead relative to other forages and the degree to which different levels of medusahead utilization impact long-term population dynamics of desired forages.

Costs and Benefits of Control and Risks of Practice Failure

Surveyed stakeholders listed a lack of understanding of the benefits, costs, and risks of practice failure as a major barrier preventing implementation of medusahead management programs. Unfortunately, our meta-analysis suggested information on costs, benefits, and risks of practice failure were largely absent from the existing literature, representing a major knowledge gap. Although the majority of studies did not report total input costs, it is likely that this information could be indirectly estimated on a project-by-project basis. A greater limitation centers on our understanding of the expected benefits of a control practice. Invasive plants can have negative and positive effects on multiple ecosystem services (e.g., livestock production, soil carbon sequestration, biodiversity, wildlife habitat) (Eviner et al., 2012). However, medusahead control studies to date, similar to work on other invasive plants (Sheley et al., 2011), have largely centered on examining how treatments influence invasive and desired plant abundance and have not assessed net benefits of control treatments on market and nonmarket services (Kyser et al., 2013; Davies et al., 2014; Uselman et al., 2014). Benefits on these services may be large, and in many systems accounting for these benefits may shift management projects from a net cost to a net benefit (de Groot et al., 2013). Future research that assesses the degree to which medusahead control influences multiple ecosystem services may be a key step toward refining our understanding and prediction of cost/benefits associated with medusahead control.

Increased livestock production is assumed to be one of the largest market benefits of invasive plant control on rangeland, particularly for species such as medusahead that produce relatively unpalatable forage containing high concentrations of silica (Bovey et al., 1961; Miller et al., 1999). Despite this assumption, the direct impact of invasive plants on pasture utilization and livestock production has rarely been directly quantified (Fuhlendorf et al., 2009) and is not known for many species, including medusahead. Part of this lack of knowledge may be because it is assumed that invasive plant control costs on rangeland will always exceed market benefits. This assumption may hold in many management situations, but there also are scenarios where control may be economically viable (Sheley et al., 2014). Understanding the direct impact of invasive plants on livestock production not only allows producers to identify cost-effective control scenarios but also provides the critical foundation for understanding how resources should be allocated in prevention and early detection/eradication efforts (Bangsund et al., 1996).

Surveyed stakeholders clearly indicated that they had multiple management objectives for controlling medusahead that extended beyond livestock production and included an array of anticipated benefits for multiple ecosystem attributes (Table 2). One of the largest challenges in quantifying benefits of various management interventions is centered on how uncertainty in practice outcome influences expected benefits (Wainger et al., 2010; Wilson et al., 2011). Namely, as the risk of practice failure increases, the expected benefit of a practice decreases. Although various optimization models have shown the value of incorporating risk of practice failure in identifying how to allocate management resources, in practice, managers often rely on experience and expert opinion to identify where and when practices are likely to have the highest probability of success (Wainger et al., 2010). Thus while producers need detailed estimates of cost and benefits for controlling medusahead and other invasive rangeland plants, it is also essential that researchers are able to identify the environmental conditions and management scenarios that primarily drive practice success or failure and use this information to forecast where and when invasive plant control efforts should be applied.

Experimental Designs to Match Stakeholder Management Realities

A major need outlined by surveyed stakeholders was simple decision tools that allow users to track and appropriately adjust medusahead management through time. Traditional experimental designs that examine how a particular tool (e.g., herbicide rate, timing, form) or combinations of tools (e.g., herbicide and seeding) influence invasive plant abundance have helped establish a critical foundation for managing invasive plants such as medusahead. However, it is widely understood among researchers and managers that these relatively simple experimental designs that examine effects of fixed treatments do not represent the iterative management and learning process that practitioners use as they manage rangeland (Briske et al., 2011). Instead, land managers address incomplete knowledge, uncertainty in treatment outcomes, and variation in environmental conditions by observing and making adjustments to management on the basis of new information generated from these observations. Adaptive management is broadly viewed as a useful general framework for managers to operate under when facing uncertainty in management outcomes and incomplete knowledge of system function (Allen et al., 2011). However, the majority of invasive plant management research, including all the studies used in our meta-analysis, does not approach application of treatments in an adaptive manner, although approaches to adaptive invasive plant management on rangeland have been proposed (Sheley et al., 2010). Given the strong progress made on understanding the basic science of medusahead control, the next logical phase is to begin to test the efficacy of treatments under an adaptive decision-making framework. In addition to having direct links to real-world management situations, these efforts should also yield more accurate understanding of the costs, benefits, and risks associated with invasive plant control efforts.

Stakeholders surveyed in this study also listed understanding outcomes of management inputs over longer time periods and at larger management scales as a major information need that would help facilitate development of long-term medusahead management programs. Typical rangeland management units can vary from 100 to over 100 000 ha, yet the average plot size for experiments included in this study was less than a hectare. Similarly, only 2 of the 26 studies incorporated in our meta-analysis tracked changes in medusahead abundance beyond 3 yr. Short-term, highly controlled, small plot research has provided a valuable foundation for understanding the potential impacts of various control treatments on medusahead. We know, however, that processes associated with invasion, plant community change, and ecosystem service provisions are tightly dependent on temporal and spatial scale (Melbourne et al., 2007). Given our relatively firm understanding of how treatments influence medusahead control in the short term and on small scales, it seems reasonable that some research effort should begin to consider how the longer temporal and larger spatial scales in which managers operate influence how various control strategies impact medusahead abundance and population dynamics. As outlined earlier, this need is probably most paramount for understanding how to use grazing animals to most effectively manage invasive rangeland plants such as medusahead. Temporal and spatial scale influence not only plant community dynamics but also animal foraging behavior and nutrition and therefore the degree to which different grazing treatments and grazing systems may impact medusahead over the long term. As the duration and spatial scale of treatments are expanded toward an operational level, there are also opportunities to examine practical limitations to medusahead management including water availability, pasture rotation constraints, drought, and how the seasonal timing of animal management activities and medusahead phenology interact to influence medusahead spread and abundance.

Implications

Invasive plant management is often one of many land management objectives on rangeland and not always the most critical or urgent objective in a given management scenario. Because managers face an array of information needs related to numerous objectives, rangeland research inherently struggles with a tradeoff between identifying general management principles that provide useful guidelines and developing detailed understanding that can be directly applied to specific but limited management scenarios (Briske, 2011). The value of systematic reviews to bridge this gap has been established (Pullin and Stewart, 2006; Briske et al., 2008; Cook et al., 2013). We have extended these efforts with this current synthesis by quantitatively evaluating the evidence on how common control tools impact medusahead abundance and integrating these results with shareholder identified information needs to generate four key themes to guide future research. Although our quantitative review focuses on medusahead and complements previously published management guidelines (Young, 1992; Miller et al., 1999; Nafus and Davies, 2014), the key identified knowledge gaps likely apply to many invasive plant management and restoration issues on rangeland. Most invasive plant management issues on rangeland are complex and treatment costs often far outweigh market benefits. Thus better understanding of the uncertainty in practice outcomes, particularly when applied under realistic management scenarios, and the net long-term benefits of these practices for multiple ecosystem services, will likely be instrumental in managing the suite of invasive plant species that threaten rangeland. As the distribution and abundance of invasive plant species expands with environmental change, addressing these knowledge gaps should help overcome key ecological and economic barriers inhibiting implementation of invasive plant management programs on rangeland and provide a positive step toward conserving the critical ecosystem services these systems provide.

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