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Authors: Stacy Davis, Jane Mangold, Fabian Menalled, Noelle Orloff, Zach Miller, and Erik Lehnhoff

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Davis, Stacy, Jane Mangold, Fabian Menalled, Noelle Orloff, Zach Miller, and Erik Lehnhoff. "A Meta-analysis of Canada Thistle *Cirsium arvense* Management." Weed Science 66, no. 4 (July 2018): 548-557. DOI:10.1017/wsc.2018.6.

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A Meta-Analysis of Canada Thistle (*Cirsium arvense*) Management

Stacy Davis, Jane Mangold, Fabian Menalled, Noelle Orloff, Zach Miller, and Erik Lehnhoff*

Although stand-alone and integrated management techniques have been cited as viable approaches to managing Canada thistle [*Cirsium arvense* (L.) Scop.], it continues to impact annual cropping and perennial systems world-wide. We conducted meta-analyses assessing effectiveness of management techniques and herbicide mechanism of action groups for controlling Canada thistle using 55 studies conducted in annual cropping systems and 45 studies in perennial systems. Herbicide was the most studied technique in both types of systems and was effective at reducing Canada thistle. However, integrated multi-tactic techniques, with or without herbicides, were more effective than sole reliance on herbicides for long-term control in both annual cropping and perennial systems. A variety of management techniques such as biocontrol, crop diversification, mowing, and soil disturbance provided similar control as herbicide. Our results suggest that many management techniques aimed at reducing Canada thistle can also improve crop yield or abundance of desired plants. This study highlights the need to devote more research to non-chemical and integrated management approaches for Canada thistle control.

* First, second, and third authors: Research Associate, Associate Professor, and Professor, Department of Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717; Fourth author: Associate Extension Specialist, Schutter Diagnostic Lab, Montana State University, Bozeman, MT 59717; Fifth author: Assistant Professor and Superintendent, Western Agricultural Research Center, Montana State University, Corvallis, MT 59828; Sixth author: Assistant Professor, Department of Entomology, Plant Pathology, and Weed Science, New Mexico State University, Las Cruces, NM 88003. Corresponding author's E-mail: stacy.davis1@montana.edu

Nomenclature: Canada thistle, *Cirsium arvense* (L.) CIRARV

Key words: Noxious weeds, invasive plants, herbicide, integrated weed management, perennial weeds, herbicide mechanism of action.

The control of and impacts resulting from perennial, invasive plants are challenging in both annual cropping systems and perennial plant communities. For example, a recent review of invasive plant control publications found that 16 of the 20 most-studied species were perennials (Kettenring and Adams 2011) and 83% of the most commonly listed noxious weeds in the United States and Canada were perennials (Skinner et al. 2000). Many perennial species spread both by seed and vegetatively, enabling effective dispersal (Hakansson 2003a). Such perennial plants also have the ability to store carbohydrate reserves in their extensive root systems. Due to these biological characteristics, perennial weeds can be persistent, difficult to manage, and tolerant of certain management techniques, such as mechanical disturbance (Hakansson 2003b).

Canada thistle (*Cirsium arvense* L.) is a perennial plant that is particularly difficult to control once established in both annual cropping and perennial systems (Tiley 2010). Canada thistle was first introduced to North America in the 1600's from Europe via contaminated grain seed, hay, and ship's ballast (Morishita 1999). It commonly invades croplands, natural areas, pastures, rangelands, and roadsides (Tiley 2010). Canada thistle was listed as a noxious weed in all but four U.S. states by 1957 (Tiley 2010), and as of 2000 it was the most frequently listed noxious weed in the United States and Canada (Skinner et al. 2000). Producers on certified organic land in the Pacific Northwest and Great Plains regions recently listed Canada thistle among the most problematic weeds (OAEC 2013; Tautges et al. 2016).

This invasive plant is an effective competitor, with a tall growth form and efficient vegetative spread aiding its rapid colonization ability and suppression of other plants (Tiley 2010). Yield losses in a variety of annual crops including barley (O'Sullivan et al. 1982), rapeseed (O'Sullivan et al. 1985), and spring wheat (Donald and Khan 1996) are associated with increased Canada thistle density. In addition, Canada thistle infestations can cause further

economic losses due to contamination of seed, grain, or straw, which results in changes in product handling, processing, and quality (Tiley 2010). Although Canada thistle is regarded as a major weed in perennial systems, there is less information published on yield losses in perennial pastures compared to annual crops (Tiley 2010). Grekul and Bork (2004) demonstrated significant grass and forb yield losses associated with increasing Canada thistle density in perennial pastures in western Canada. Furthermore, Canada's thistle's prickly mature foliage can reduce pasture productivity by deterring livestock from grazing in infested areas (Tiley 2010).

Although stand-alone and integrated management techniques have been cited as viable approaches to managing Canada thistle (Donald 1990), it continues to invade and persist in temperate regions of the world. Carefully reviewing and systematically summarizing results from previous studies may help refine management strategies for Canada thistle. A statistical tool useful for achieving this goal is meta-analysis, i.e., the systematic and quantitative review and synthesis of previous studies (Koricheva and Gurevitch 2014). For example, through a meta-analysis of 52 studies, Lutman et al. (2013) determined that mechanical cultivation and time of seeding were the most efficient non-chemical approaches to manage blackgrass (*Alopecurus myosuroides* Huds.). Additionally, a meta-analysis on downy brome (*Bromus tectorum* L.) management indicated that a variety of control methods reduced short-term abundance of downy brome, but only those that included herbicide or revegetation led to long-term control (Monaco et al. 2017). Finally, a recently completed meta-analysis of management of Canada thistle and field bindweed (*Convolvulus arvensis* L.) in organic cropping systems showed that integrating two or more management strategies generally caused greater reductions in weed abundance than any method used alone (N Orloff, personal communication). Meta-analyses can also identify knowledge gaps and potential ways to improve experimental approaches. For example, a recent

review found that most experimental approaches assessing weed control of invasive plants evaluated efficacy of management techniques on short time frames (<1 year) and rarely included impacts on desirable vegetation or evaluations of control costs (Kettenring and Adams 2011).

We conducted a meta-analysis to review and summarize results from previously published studies involving Canada thistle management in annual cropping and perennial systems. Our objectives were to 1) assess short- and long-term effectiveness of management techniques for controlling Canada thistle, 2) compare short- and long-term effectiveness of different herbicide mechanism of action (MOA) groups for controlling Canada thistle, 3) determine if and how management techniques for Canada thistle control impact crop yield (annual cropping systems) or abundance of desired plants (perennial systems), and 4) identify knowledge gaps. These objectives were conducted separately for annual cropping systems (row crop and fallow fields) and perennial systems (pasture, rangeland, natural areas, etc.).

Materials and Methods

Literature Search and Study Inclusion. In December 2015 we conducted a literature search for Canada thistle using the Web of Science® (1864-2015) and Agricola® (1927-2015) databases. We used the keywords “*Cirsium arvense*,” “*Carduus arvensis*,” “Canada thistle,” “creeping thistle,” “Californian thistle,” and “field thistle.” We limited our search to articles written in English.

Following guidelines by Koricheva et al. (2013), all references underwent the following filtering process for their inclusion into the meta-analysis: (1) duplicate references from the two databases were removed, (2) abstracts and titles of retrieved articles were examined and clearly irrelevant literature (e.g., patents, studies about ecology or biology with no control treatments,

medical topics, genetics studies, pollination studies) was removed, and (3) full text of selected articles was examined and studies were included that met our pre-established inclusion criteria. Specifically, we included replicated field studies that assessed the relative efficacy of stand-alone or integrated weed management techniques taking place in annual cropping or perennial systems. We limited annual cropping system studies to cooler, temperate climatic regions specified as those that grew crops listed by the US Department of Agriculture state agriculture overview for the Northern Great Plains states (defined as Montana, Nebraska, North Dakota, South Dakota, and Wyoming): wheat (*Triticum aestivum* L.), hay (*Medicago sativa* L.), barley (*Hordeum vulgare* L.), peas (*Pisum sativum*), potatoes (*Solanum tuberosum*), lentils (*Lens culinaris*), corn (*Zea mays* L.), beans (*Phaseolus vulgaris*), canola (*Brassica napus* L.), safflower (*Carthamus tinctorius*), oats (*Avena spp.*), sugar beets (*Beta vulgaris*), sunflower (*Helianthus annuus* L.), sorghum (*Sorghum bicolor* (L.) Moench ssp. *bicolor*), millet (*Panicum miliaceum* L.), legumes (*Medicago sativa* L.), mustard (*Brassica nigra* (L.) W.D.J. Koch; *Sinapis alba* L.), and flaxseed (*Linum usitatissimum* L.) (USDA 2017). Perennial systems included rangelands, pastures, lawns, alfalfa, hay fields, and natural areas world-wide.

Studies utilizing herbicides were included only if the applied herbicide was approved for use according to Shaner (2014) and if it was applied within recommended rates (Greenbook 2017; Shaner 2014). We followed terminology from Shaner (2014) and did not consider herbicides that had an unclassified MOA (e.g., sodium chlorate). We included studies with control/treatment comparisons that published quantitative response measurements for aboveground density, cover, biomass, frequency, survival, or percent control (measured from 0-100%) of Canada thistle. Responses needed to be from established Canada thistle populations as

opposed to populations established artificially for testing purposes. The filtering process was conducted by a single author (S. Davis).

Data Extraction and Synthesis. Following Gurevitch and Hedges (2001), we recorded means, measures of variation, and sample sizes for both control and treatment plots from published tables, within the text, or derived from published figures using WebPlotDigitizer (Rohatgi c2010-2017). Means included quantitative response measurements for aboveground density, cover, biomass, frequency, survival, or percent control of Canada thistle. We extracted additional information on type of system (annual versus perennial), study duration, and details of the treatment applied (e.g., herbicide type and rate, herbicide MOA group). Herbicide MOA groups followed the classification used in Shaner (2014) and were as follows: 2 (Acetolactate Synthase (ALS) or Acetohydroxy Acid Synthase (AHAS) Inhibitors), 4 (Synthetic Auxins), 5 (Inhibitors of photosynthesis at photosystem II site A), 6 (Inhibitors of photosynthesis at photosystem II site B), 9 (Inhibitor of 5-enolpyruvyl-shikimate-3-phosphate synthase (EPSPS)), 11 (Inhibitors of carotenoid biosynthesis (unknown target)), 27 (Inhibitors of 4-hydroxyphenyl-pyruvatedioxygenase (4-HPPD)). We included a “mix” herbicide MOA group, which we defined as an herbicide application including two or more herbicides from different groups. We also extracted data, when available, on crop yield or abundance of desired plants to examine how Canada thistle management techniques impacted them.

Following Gurevitch and Hedges (2001), we developed a series of criteria to systematically extract data from the literature. If there were multiple types of response measurements within a study (e.g., density and cover), we selected one response type using a ranking process to avoid issues of non-independence. We ranked response measurements based on a pre-determined order of importance: 1) biomass, 2) cover, 3) density, 4) frequency, 5)

survival, and 6) percent control. Oftentimes, percent control response measurements did not include means for non-treated plots; therefore we assumed 0% control in non-treated plots. Additionally, percent control was transformed to the same scale as weed abundance measurements (i.e., biomass, cover, density, frequency, or survival) by subtracting percent control from 100. In this metric, lower numbers indicated more successful management.

For each published article, if more than one site or treatment were assessed, data were extracted from each situation being tested. For multifactorial studies, we considered the response to each treatment as an independent data point (Gurevitch and Hedges 2001). For example, if an article compared five different types of herbicide active ingredients applied at two different rates, we extracted data for each herbicide active ingredient and rate combination, for a total of 10 data points. Although this meant the same control group mean was included for more than one data point, it allowed us to maximize use of existing valuable data on effectiveness of management techniques (Gurevitch and Hedges 2001).

When multiple articles reported results on the same study across varying years, we used the data only once by extracting data from the latest set of observations. Many land managers apply management techniques every year for multiple years in a row, but in order to accurately compare short- and long-term control of Canada thistle, we only used response measurements that considered a single year of treatment. If responses to a single year of treatment were measured over multiple dates, we extracted data from two defined time periods (less than one year after treatment and one year or more after treatment) when possible and conducted separate analyses to compare short- versus long-term control. If there were repeated measures within our defined time periods, we only used the response from the longest time period since treatment (Gurevitch and Hedges 2001).

Data Analysis. For each data point, the effect size of a treatment was calculated as the log response ratio (lnR), where

$$\ln R = \ln(X^E/X^C) = \ln X^E - \ln X^C \quad [1]$$

and X^E and X^C are means of experimental (treated) and control (non-treated) groups, respectively (Hedges et al. 1999). This variable quantifies the proportionate change that results from an experimental treatment and represents a meaningful approach to summarize and combine results of different studies (Hedges et al. 1999). We selected the response ratio for our analysis because it can be estimated without knowledge of sample sizes or variances (Adams et al. 1997). An example of an effect size measurement that utilizes measures of variance includes the standardized difference in means (e.g., Hedge's D) (Koricheva et al. 2013). However, since many of our studies did not report measures of variation, we used the response ratio as our effect size measurement. Only 22% of data points from annual cropping systems and 2% of data points from perennial systems reported measures of variation.

The response ratio cannot be calculated when data points have response measurements equal to zero because one cannot take a logarithm of a zero value (Koricheva et al. 2013). Therefore, 10 data points from annual cropping systems and 11 data points from perennial systems were excluded from the analysis (<3% of data for each system type). Although we could not include these data points, using the response ratio as our effect size allowed us to include a large amount of data that did not report measures of variation.

We paired our response ratio with a nonparametric bootstrapping approach using a simplified weighting scheme. Meta-analyses using Hedge's D as the effect size metric weight each effect size based on their relative sensitivity to measures of variance (Koricheva et al.

2013). However, since most of our studies lacked information about variance, we weighted each response ratio using sample sizes with the function F_N , where

$$F_N = (n_E \times n_C) / (n_E + n_C) \quad [2]$$

and n_E and n_C represent the number of replicates for the experimental (treated) and control (non-treated) groups, respectively (Adams et al. 1997). We used bootstrapping methods to calculate 95% confidence intervals around the pooled effect size mean with 1,000 iterations for individual management techniques or herbicide MOA groups (Adams et al. 1997). Individual management techniques or herbicide MOA groups were considered effective at managing Canada thistle if the mean response ratio was negative and the 95% confidence interval did not overlap zero (Adams et al. 1997; Gurevitch et al. 1992). For example, a 50% reduction in Canada thistle relative to a control group is equivalent to an effect size of -0.7. Mean response ratios from different management techniques or herbicide MOA groups were considered to be different from one another if their 95% confidence intervals did not overlap (de Graaff et al. 2006; Ferreira et al. 2015). Management techniques or herbicide MOA groups that had only one data point were included in figures to note knowledge gaps and should not be compared statistically to other management techniques or herbicide MOA groups because confidence intervals could not be calculated. All summaries and analyses were conducted in R statistical software (version 3.3.2), including the “plyr”, “ggplot2”, and “cowplot” packages (R Core Team 2016).

We conducted separate meta-analyses corresponding to each objective. First, we examined management techniques used for Canada thistle control in annual cropping and perennial systems. Management techniques included biocontrol, burn, competition, crop diversification, fertilizer, herbicide, herbicide integrated, mowing, mulch, non-herbicide integrated, soil disturbance, and water manipulation (Table 1). We included the categories of

herbicide integrated and non-herbicide integrated to examine the effectiveness of integrated multi-tactic techniques, with or without herbicides. For our analyses in annual cropping and perennial systems, we examined management at different time periods by conducting two meta-analyses for each system, one for responses measured <1 year after treatment and another for responses measured ≥ 1 year after treatment. Next, we examined efficacy of different herbicide MOA groups (<1 year after treatment and ≥ 1 year after treatment). We did not compare additional specifics of individual management techniques (e.g., timing, types of biocontrol agents, herbicide rates) because this level of detail was outside the scope of our questions of interest and there was insufficient replication of specific practices within management techniques to adequately compare them. Finally, we compared the effect of management techniques on crop yield (annual) or abundance of desired plants (perennial). A positive response ratio indicated an increase in yield or abundance with treatment, while 95% confidence intervals overlapping zero indicated the management technique had no effect (Gurevitch et al. 1992).

Complete bibliographies of the articles used in our annual cropping and perennial system analyses are given in Supplemental Appendices 1 and 2. Information from each article used in our meta-analysis, including study location, system description, management techniques, herbicide MOA groups (if applicable), and study duration grouping, is shown in Supplemental Tables 1 and 2.

Results and Discussion

Canada Thistle Management in Annual Cropping Systems. We extracted data from 55 articles published between 1957 and 2015, resulting in 650 total data points (Figure 1). The majority of studies took place in the United States (33 articles) and Canada (9 articles), while the

remaining took place in Denmark, England, Germany, Hungary, India, Iran, New Zealand, Norway, Poland, Serbia, and Sweden. Nearly three quarters (74%) of data points evaluated short-term efficacy of Canada thistle management (<1 year).

All management techniques studied were effective at reducing Canada thistle in annual cropping systems when measured <1 year after treatment (Figure 2a). However, herbicide integrated management techniques were most effective for short-term control (Figure 2a). Herbicide, herbicide integrated, and soil disturbance were more effective than biocontrol and crop diversification (Figure 2a). Many management techniques were also effective ≥ 1 year after treatment. Biocontrol, crop diversification, herbicide, herbicide integrated, mowing, non-herbicide integrated, and soil disturbance all reduced Canada thistle ≥ 1 year after treatment (Figure 2b). Similar to effects <1 year after treatment, herbicide integrated management techniques were more effective than herbicide alone ≥ 1 year after treatment (Figure 2b). Additionally, herbicide integrated management techniques were similar to non-herbicide integrated management techniques ≥ 1 year after treatment (Figure 2b). Fertilizer had no effect on Canada thistle ≥ 1 year after treatment (Figure 2b). The availability of data for competition as a management technique in annual cropping systems was insufficient, with only one data point reporting treatment effects both <1 and ≥ 1 year after treatment.

Although herbicide was the most studied management technique (79% of data points), other less studied management techniques were equally or more effective at controlling Canada thistle in annual cropping systems. For example, soil disturbance was as effective as herbicide <1 year after treatment but has not been studied to the extent that control via herbicide has. Furthermore, biocontrol, crop diversification, mowing, and soil disturbance all had the same level of effectiveness as herbicide ≥ 1 year after treatment. Only two data points in our meta-

analysis evaluated the long-term effectiveness of non-herbicide integrated management techniques, but these techniques resulted in improved control of Canada thistle versus herbicide alone (Figure 2b), highlighting the potential benefits of non-chemical multi-tactic strategies for Canada thistle control.

Our meta-analysis also indicated that herbicide integrated management techniques resulted in greater reductions in Canada thistle than herbicide applied alone both <1 year and ≥ 1 year after treatment (Figure 2a, 2b). Herbicide integrated management techniques examined across both time periods included herbicide + fertilizer (3 data points), herbicide + mowing (14 data points), herbicide + soil disturbance (40 data points), and herbicide + soil disturbance + fertilizer (3 data points). Compared to herbicide used as a stand-alone technique, integrating herbicides with additional management techniques can help reduce crop injury and decrease the selective pressure towards the selection of herbicide resistance, while providing control of invasive perennial weed species (Miller 2016).

All herbicide MOA groups reduced Canada thistle when measured <1 year after treatment (Figure 3a), while only half of the MOA groups tested ≥ 1 year after treatment were effective (Figure 3b). Less than one year after treatment, herbicide MOA groups 4, 6, 9, 11, 27, or mixes of MOA groups reduced Canada thistle more than herbicide MOA group 2 (Figure 3a). One year or more after treatment, herbicide MOA groups 4, 5 and 9 were effective at reducing Canada thistle (Figure 3b). However, herbicide MOA group 9 was slightly more effective than MOA group 4 (Figure 3b). Herbicide MOA group 4 (i.e., synthetic auxins) was most frequently tested ≥ 1 year after treatment ($n=37$) and included 2,4-D (32%), picloram (26%), and clopyralid (16%). Other MOA group 4 herbicides included dicamba, quinclorac, and MCPA (26%). Herbicide MOA group 5 (i.e., inhibitors of photosynthesis at photosystem II site A) assessed ≥ 1

year after treatment all consisted of atrazine in corn fields (n=6) (Parochetti 1974). Herbicide MOA group 9 (i.e., inhibitors of EPSPS, glyphosate) was used in 24 data points evaluated ≥ 1 year after treatment. Herbicide MOA groups 2, 11, or mixes of MOA groups did not provide Canada thistle control ≥ 1 year after treatment. Two of ten data points for the mix treatment had a positive effect size (i.e., increased Canada thistle). These treatments were bromoxynil + MCPA and glyphosate + bromoxynil + MCPA used in spring wheat (Carlson and Donald 1988). Overall, results from short-term studies suggest that all herbicide MOA groups studied have similar effectiveness. However, if the goal of the land manager is to reduce the frequency of herbicide applications, herbicide MOA groups 4, 5, and 9 are promising options for longer-term control of Canada thistle in annual cropping systems.

Canada thistle causes significant yield losses in the northern part of North America (Tiley 2010), but our results suggest that management options can help reduce its impacts. In our meta-analysis, 90 data points reported on how various management techniques for Canada thistle control were associated with improved crop yield of barley, canola, corn, rapeseed, spring wheat, sugar beets, and winter wheat (Figure 4). These techniques included biocontrol, crop diversification, herbicide, herbicide integrated, non-herbicide integrated, and soil disturbance. Biocontrol, herbicide, and herbicide integrated management techniques were similarly associated with increased crop yield (Figure 4). Crop diversification and non-herbicide integrated management techniques were associated with increased crop yield more than biocontrol and herbicide (Figure 4). However, herbicide was the only management technique that had more than three data points recording crop yield, emphasizing the need to include measurements of crop yield in study design. The availability of data for fertilizer as a management technique was

insufficient to make comparisons with other techniques, with only one data point reporting treatment effects.

Canada Thistle Management in Perennial Systems. We extracted data from 45 articles published between 1958 and 2015, resulting in 376 total data points (Figure 1). The majority of these studies took place in the United States (28 articles) and New Zealand (11 articles), while the remaining took place in Australia (1 article), Canada (2 articles), Czech Republic (1 article), Turkey (1 article), and the United Kingdom (1 article). Perennial systems studied included alfalfa fields, grass for seed, natural areas, pastures, rangelands, and roadsides. More than half of data points (58%) evaluated short-term efficacy of Canada thistle management (<1 year).

Our meta-analysis revealed that biocontrol, competition, herbicide, herbicide integrated, mowing, mulch, and non-herbicide integrated management techniques reduced Canada thistle <1 year after treatment (Figure 5a). Herbicide and herbicide integrated management techniques were most effective at reducing Canada thistle, compared to all other techniques (Figure 5a). Fertilizer had no effect on Canada thistle control, whereas water manipulation increased the density of Canada thistle <1 year after treatment (Figure 5a). The three water manipulation data points were from low, medium, and high levels of irrigation on plots with forage species; all levels of irrigation resulted in an increase in density of Canada thistle (Thrasher et al. 1963). Only one data point existed for the impact of burning on Canada thistle, so comparisons to other management techniques should not be made.

Many management techniques that were effective at reducing Canada thistle <1 year after treatment were also effective ≥ 1 year after treatment. These included biocontrol, herbicide, herbicide integrated, and mowing (Figure 5b). Although herbicide was equally effective as herbicide integrated <1 year after treatment, herbicide integrated was more effective than

herbicide alone ≥ 1 year after treatment (Figure 5b). Mowing was as effective as herbicide in controlling Canada thistle ≥ 1 year after treatment (Figure 5b). Mowing techniques included removing all vegetation to 5 cm using a sickle bar when Canada thistle was at early bud stage in a pasture (Grekul and Bork 2007), mowing alfalfa fields twice a year for hay (Hodgson 1958), and using a rotary mower set at 5 cm when Canada thistle was at bud stage in a pasture (Amor and Harris 1977). Even though competition decreased Canada thistle < 1 year after treatment (Figure 5a), it had no effect on Canada thistle ≥ 1 year after treatment (Figure 5b).

Similar to our annual cropping system results and the findings of other meta-analyses (Kettenring and Adams 2011), herbicide was the most studied management technique in perennial systems (61%). However, other management techniques were equally or more effective than herbicide for long-term control. Specifically, mowing was as effective as herbicide while herbicide integrated management techniques were more effective than herbicide applied alone ≥ 1 year after treatment. Herbicide integrated management techniques that resulted in long-term control included herbicide + burn (1 data point), herbicide + competition (2 data points), herbicide + soil disturbance (1 data point), herbicide + competition + mowing (1 data point), and herbicide + competition + soil disturbance (1 data point). While herbicides are the primary method of weed control in most rangelands, this study emphasizes the need to develop integrated weed management programs to achieve long-term control of weeds and healthy plant communities (DiTomaso 2000).

All herbicide MOA groups reduced Canada thistle < 1 year and ≥ 1 year after treatment (Figure 6a, 6b). Several herbicide MOA groups showed similar effectiveness in controlling Canada thistle. In particular, herbicide MOA groups 2, 4, and mixes of MOA groups were similar in effectiveness < 1 year after treatment (Figure 6a). Herbicide MOA group 4 and mixes

of MOA groups showed higher effectiveness than herbicide MOA groups 5 and 6 <1 year after treatment (Figure 6a). Herbicide mixes included imazamox + bentazon, imazethapyr + bentazon, MCPB + bentazon, clopyralid + chlorsulfuron, and 2,4-D + chlorsulfuron. One year or more after treatment, herbicide MOA groups 2, 4, 9, and mixes of MOA groups were similar in effectiveness (Figure 6b). Herbicide mixes included dicamba + diflufenzopyr, 2,4-D + chlorsulfuron, and 2,4-D + metsulfuron. Herbicide MOA group 9 was represented in our meta-analysis by only six data points that measured control ≥ 1 year after treatment. This group is likely seldom used in pastures and rangelands because it includes non-selective products which could injure desired perennial vegetation. Data for herbicide MOA group 6 ≥ 1 year after treatment and MOA group 11 in both time periods was insufficient to make comparisons with other groups, with only one data point for each MOA group reporting treatment effects.

Similar to our results in annual cropping systems, herbicide MOA group 4 was the most studied in perennial systems, with 81% of data points using this group across both time periods. Additionally, the majority of studies using mixes of MOA groups had group 4 as one of the ingredients (73% of data points). Herbicide MOA group 4 contains herbicides such as 2,4-D, dicamba, clopyralid, MCPA, and picloram that are considered important tools for managing perennial invasive species in rangelands and pastures (DiTomaso 2000; Morishita 1999). Common MOA group 4 herbicides used in studies in our meta-analysis included clopyralid (19%), 2,4-D (18%), dicamba (17%), a mix of two or more MOA group 4 herbicides (17%), and picloram (15%). Other MOA group 4 herbicides making up 15% of use in studies included aminopyralid, MCPB, and MCPA. In spite of the emphasis on MOA group 4 in past research, other MOA groups were just as effective at reducing Canada thistle ≥ 1 year after treatment (e.g., groups 2 and 9).

Both competition and herbicide were similarly associated with increased abundance of desired plants in perennial systems (competition mean $\ln R = 0.45$, 95% CI: 0.21 to 0.67, $n=5$; herbicide mean $\ln R = 0.20$, 95% CI: 0.08 to 0.32, $n=27$), as demonstrated by thirty-two data points measuring alfalfa yield, seed yield, and grass biomass. For example, decreasing row spacing of alfalfa was associated with an increase in alfalfa yield and a reduction in Canada thistle density (Celebi et al. 2010). A total of three articles that utilized herbicides also recorded abundance of desired plants with contrasting results. Mesbah and Miller (2005) found an increase in alfalfa seed yield after applying a variety of herbicides (18 data points), and Gallagher and Vandeborn (1976) observed both increases and decreases in creeping red fescue (*Festuca rubra* L.) seed yield after applying herbicides (seven data points). In contrast, Krueger-Mangold et al. (2002) observed a decrease in desired grass biomass after treating natural areas in the fall with glyphosate, a non-selective herbicide (two data points). It is important to note that other plant community components and ecosystem services may also change as a result of management efforts. For example, abundance of desired forbs may decrease as a result of broadleaf herbicide use (Ortega and Pearson 2010). Although no data points in our meta-analysis examined the response of native forbs to Canada thistle management techniques, the potential non-target effects on native forbs with broadleaf herbicides is an important concern.

Incorporating herbicide use with other weed management strategies may help minimize such non-target impacts in perennial systems (Crone et al. 2009).

General Management Recommendations. Our meta-analysis provides several general management recommendations for Canada thistle. First, in both annual cropping and perennial systems, land managers should consider integrating management techniques for enhanced long-term control of Canada thistle, as this approach proved to be more effective than solely applying

herbicides. Second, despite herbicide being the most studied management technique, a variety of other management techniques resulted in similar control of Canada thistle in the short- and long-term in annual cropping and perennial systems. This emphasizes the need to re-focus weed science research priorities by investigating alternative and integrated control methods more often. Third, herbicide MOA groups 4, 5, or 9 can be used for long-term control of Canada thistle in annual cropping systems. Finally, a variety of herbicide MOA groups can be used for long-term control of Canada thistle in perennial systems including groups 2, 4, 5, 9, and mixes of MOA groups.

Future Research. First, our meta-analysis had limited data on certain non-chemical management techniques, such as burning, mulch, and water manipulation. However, some of these management techniques had negative effect sizes, suggesting these could be promising techniques for Canada thistle control. Additional management techniques, such as grazing, were not examined due to lack of papers addressing these. Therefore, increasing the amount of research devoted to non-chemical and integrated management techniques in annual cropping and perennial systems may help provide a broader range of management recommendations for Canada thistle control. Second, because short-term studies could misrepresent the impact of a management technique on a perennial species, we encourage researchers to conduct long-term evaluations on approaches to control Canada thistle. Finally, our meta-analysis, along with others (Koricheva and Gurevitch 2014; Philibert et al. 2012), highlights the need to include such basic information on means, measures of variation, and sample sizes in published articles related to invasive species management (Gurevitch and Hedges 2001; Gurevitch et al. 1992). Additionally, researchers should consider the importance of measuring not only weed control but also crop yield and abundance of desired plants, as well as other ecosystem services.

Acknowledgements

The authors would like to thank the Montana Noxious Weed Trust Fund and the Montana Wheat and Barley Committee for funding this research. We would like to thank Sean MacKenzie for statistical analysis help.

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Tables

Table 1. Descriptions of management techniques used in articles included in the meta-analysis of Canada thistle. The number of data points associated with each type of system is indicated.

Management technique	Description	Annual cropping	Perennial
Biocontrol	Biological control using insects or pathogens	24	20
Burn	Prescribed fire	0	1
Competition	Any method attempting to increase competitive ability including manipulating row spacing or revegetation	2	48
Crop diversification	Adding cover crops or increasing crop rotation to a cropping system	17	0
Fertilizer	Soil amendments including fertilizer or manure applied	2	7
Herbicide	Applying herbicides	512	228
Herbicide integrated	Any combination of two or more management techniques with at least one method utilizing herbicides	60	30
Mowing	Mechanical mowing or clipping	12	11
Mulch	Use of either plastic or organic mulches	0	3

Non-herbicide integrated	Combination of two or more management techniques, none including herbicides	2	25
Soil disturbance	Mechanical control methods including tillage, cultivation, hoeing, or harrowing	19	0
Water manipulation	Changing water availability through irrigation	0	3

Figures

Figure 1. Flow diagram depicting criteria applied during literature screening portion of the meta-analysis of Canada thistle management. In each box, “n” is the number of articles described in that step.

Figure 2. Mean effect size (lnR) and 95% confidence intervals for Canada thistle abundance measured (a) <1 year or (b) ≥ 1 year after treatment in annual cropping systems as a function of management techniques. For each management technique, the number next to the confidence interval represents the number of data points that was used to calculate the mean.

Figure 3. Mean effect size (lnR) and 95% confidence intervals for Canada thistle abundance measured (a) <1 year or (b) ≥ 1 year after treatment in annual cropping systems as a function of herbicide mechanism of action groups. For each group, the number next to the confidence interval represents the number of data points that was used to calculate the mean. Groups are as follows: 2= ALS or AHAS inhibitors; 4= synthetic auxins; 5= inhibitors of photosynthesis at photosystem II site A; 6=inhibitors of photosynthesis at photosystem II site B; 9=inhibitor of EPSPS; 11=inhibitors of carotenoid biosynthesis; 27 = inhibitors of 4-hydroxyphenyl-pyruvate dioxygenase (4-HPPD); and mix= includes two or more herbicides from different groups.

Figure 4. Mean effect size (lnR) and 95% confidence intervals for crop yield in annual cropping systems as a function of Canada thistle management techniques. For each management technique, the number next to the confidence interval represents the number of data points that was used to calculate the mean.

Figure 5. Mean effect size (lnR) and 95% confidence intervals for Canada thistle abundance measured (a) <1 year or (b) ≥1 year after treatment in perennial systems as a function of management techniques. For each management technique, the number next to the confidence interval represents the number of data points that was used to calculate the mean.

Figure 6. Mean effect size (lnR) and 95% confidence intervals for Canada thistle abundance measured (a) <1 year or (b) ≥1 year after treatment in perennial systems as a function of herbicide mechanism of action groups. For each group, the number next to the confidence interval represents the number of data points that was used to calculate the mean. Groups are as follows: 2= ALS or AHAS inhibitors; 4= synthetic auxins; 5= inhibitors of photosynthesis at photosystem II site A; 6=inhibitors of photosynthesis at photosystem II site B; 9=inhibitor of EPSPS; 11=inhibitors of carotenoid biosynthesis; and mix= includes two or more herbicides from different groups.

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Appendix S2. References used in meta-analysis of Canada thistle management in perennial systems:

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- 1 Table S1. Article information used in meta-analysis of Canada thistle management in annual cropping systems. Articles that had
- 2 information on crop yield are indicated by an * next to the citation.

Citation	Study location	Annual cropping system description	Management technique	Herbicide groups	Study duration	
					<1 year	≥1 year
Armel et al. 2005	Delaware, United States	corn	herbicide	4, 27, mix	X	
Asadi et al. 2013 *	Mashhad, Iran	winter wheat	biocontrol	na	X	
Bicksler and Masiunas 2009	Illinois, United States	fallow, cover crop- buckwheat, sudangrass, or sudangrass-cowpea mix	crop diversification	na	X	X
Blasko and Nemeth 2006	Hungary	corn	herbicide	2, mix	X	X
Bondarenko 1957	Ohio, United States	fallow	herbicide	11		X
			herbicide integrated	11		X
Brosten and Sands 1986	Montana, United States	fallow	biocontrol	na	X	X
Carlson and Donald 1988	North Dakota, United States	spring wheat	herbicide	9, mix	X	X
Carson and Bandeen 1975	Ontario, Canada	fallow	herbicide	4, 5	X	
Causey and Webb 1990	Delaware, United States	corn	herbicide	mix	X	

Curtis and Haagsma 1986	Alberta, Canada	wheat, barley	herbicide	4	X	X
Darwent et al. 1994	Alberta, Canada	barley, canola-barley-barley, lentil-barley-barley, wheat-barley-barley, field pea-wheat	herbicide	9		X
Davies and Orson 1987	Norfolk and Essex, England	winter wheat	herbicide	2, 4	X	
	Cambridge and March, England	fallow	herbicide	2, 4		X
Derscheid et al. 1961	South Dakota, United States	oats	herbicide	4	X	X
			herbicide integrated	4	X	
Donald 1993	North Dakota, United States	fallow	herbicide	4, 9	X	
Donald and Prato 1992a	North Dakota, United States	spring wheat	herbicide	4, mix	X	
Donald and Prato 1992b *	North Dakota, United States	spring wheat	herbicide	2, 4	X	
Faravani and Khlaghani 2004	Khorasan, Iran	wheat	herbicide	9, 2	X	
Glenn and Heimer 1994 *	Maryland, United States	corn	herbicide	2, 4, 9, mix	X	
Graglia et al. 2006	Slagelse, Denmark	grass/clover, spring barley	mowing	na		X
		red clover, spring barley	soil disturbance	na		X
Gronwald et al. 2002	Minnesota, United States	soybean	biocontrol	na	X	

Hodgson 1958 *	Montana, United States	spring wheat	fertilizer	na		X
		fallow, spring wheat, peas	herbicide	4		X
		spring wheat, potatoes and corn	herbicide integrated	4		X
Hoelt et al. 2001	Minnesota, United States	soybean	biocontrol	na	X	
			herbicide	6	X	
Howatt et al. 2006	North Dakota, United States	spring wheat	herbicide	9, mix	X	
Kirkland 1977 *	Saskatchewan, Canada	fallow	herbicide	9	X	
			herbicide integrated	9	X	
Kluth et al. 2005	Lower Saxony, Germany	fallow	biocontrol	na	X	
Kwiatkowski 2009	Lublin, Poland	spring barley	crop diversification	na	X	
Lym and Deibert 2005	North Dakota, United States	fallow	herbicide	4, mix	X	X
McKay 1959	Idaho, United States	potatoes	competition	na		X
		spring wheat	fertilizer	na		X
		spring wheat	herbicide	4		X
		spring wheat-alfalfa	herbicide integrated	4		X
McKone 1989	Montana, United States	barley	herbicide	2, 4	X	
Miller 1987 *	Wyoming, United States	barley	herbicide	2, 4, mix	X	

Miller and Lym 1998	North Dakota, United States	corn, soybean	herbicide	4, mix	X	
			soil disturbance	na	X	
Miller et al. 1989 *	Wyoming, United States	barley	herbicide	4, 5, mix	X	
Miller et al. 1994 *	Wyoming, United States	sugarbeets	herbicide	4	X	
Naish 1975	New Zealand	fallow	herbicide	4	X	
O'Donovan et al. 2001 *	Alberta, Canada	barley-canola	herbicide	4	X	
O'Sullivan 1982	Alberta, Canada	barley and wheat	herbicide	2	X	
O'Sullivan and Kossatz 1982 *	Alberta, Canada	rapeseed	herbicide	4	X	
O'Sullivan and Kossatz 1984a *	Alberta, Canada	rapeseed	herbicide	4	X	
O'Sullivan and Kossatz 1984b *	Alberta, Canada	barley	herbicide	4	X	
Parochetti 1974	Maryland, United States	corn	herbicide	5, 11	X	
Rabcewicz 1995	Alnarp, Sweden	fallow	soil disturbance	na	X	
Renner 1991	Michigan, United States	sugarbeets	herbicide	4	X	
Selleck and Baird 1981	Pennsylvania, United States	corn and soybeans	herbicide	9, mix	X	
Singh and Malik 1992	Hisar, India	fallow	herbicide	4	X	
Terry and Wilson 1964	Essex, England	winter wheat	herbicide	5	X	

Thomsen et al. 2015 *	As, Norway	spring wheat	crop diversification	na		X
			non-herbicide integrated	na		X
Tolimir et al. 2006 *	Belgrade, Serbia	corn	soil disturbance	na	X	
Warden 1964	South Dakota, Minnesota, and Wisconsin United States	fallow	herbicide	4	X	
	Montana, United States	winter wheat	herbicide	4		X
	Minnesota, United States	oats	herbicide	4		X
Warnes 1974	Minnesota, United States	fallow-corn	herbicide	4	X	X
			herbicide integrated	4	X	X
			soil disturbance	na	X	
Wedryk and Cardina 2012	Ohio, United States	fallow	competition	na	X	
Westra and D'Amato 1988	Colorado, United States	winter wheat	herbicide	2, 4, 9, mix	X	
Zimdahl and Foster 1974	Colorado, United States	fallow	herbicide	4, 5, 9, mix	X	X
Zimdahl and Foster 1979	Colorado, United States	fallow	herbicide	4, 5, 9, mix	X	
Zimdahl and Foster 1993	Colorado, United States	fallow	herbicide	2, 4, 9	X	

Zuris et al. 1987	Nebraska, United States	winter wheat-fallow	herbicide	2	X	X
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12 Table S2. Article information used in meta-analysis of Canada thistle management in perennial systems. Articles that had information
13 on desired plant yield are indicated by an * next to the citation.

Citation	Study location	Perennial system description	Management technique	Herbicide groups	Study duration	
					<1 year	≥1 year
Almquist and Lym 2010	Minnesota, United States	range	herbicide	4	X	X

Amor and Harris 1977	Victoria, Australia	pasture	herbicide	4, 9, 11	X	X
			mowing	na	X	X
Beck 1988	Colorado, United States	pasture	herbicide	4, mix	X	X
Beck et al. 1989	Colorado, United States	pasture	herbicide	4	X	X
Biesboer et al. 1994	Minnesota, United States	natural area	competition	na	X	X
Bixler et al. 1991	Washington, United States	natural area, pasture	herbicide	2, 4, mix	X	X
Boerboom and Wyse 1988	Minnesota, United States	pasture	herbicide	6		X
Bourdot et al. 1993	Canterbury, New Zealand	pasture	biocontrol	na	X	X
Bourdot et al. 2004	Canterbury, New Zealand	pasture	biocontrol	na	X	
Bourdot et al. 2006	Canterbury, New Zealand	pasture	biocontrol	na		X
Bultsma et al. 1992	Wyoming, United States	range	herbicide	4		X

Celebi et al. 2010 *	Van, Turkey	alfalfa	competition	na		X
Clements et al. 2012	Southampton, England	pasture	fertilizer	na	X	
Derscheid et al. 1961	South Dakota, United States	pasture	herbicide integrated	4	X	
			non-herbicide integrated	na	X	
Enloe et al. 2007	North Dakota, Colorado, and Wyoming, United States	range, pasture	herbicide	4, mix		X
Foote et al. 1970	Minnesota, United States	roadside	herbicide	4		X
Gaisler et al. 2008	Liberec, Czech Republic	natural area	mowing	na	X	
			mulch	na	X	
Gallagher and Vanden Born 1976 *	Alberta, Canada	grass for seed	herbicide	4	X	X
Gramig and	North Dakota,	range	herbicide integrated	4		X

Ganguli 2015	United States					
Grekul and Bork 2007	Alberta, Canada	pasture	fertilizer	na	X	
			herbicide	4		X
			herbicide integrated	4	X	
			mowing	na		X
			non-herbicide integrated	na	X	
Harrington et al. 2014	Washington, United States	meadow	herbicide	4		X
Hartley and James 1979	Hamilton, New Zealand	pasture	herbicide integrated	4	X	
			non-herbicide integrated	na	X	
Hartley and Thomson 1982	Normany, New Zealand	pasture	herbicide	4	X	
			mowing	na	X	
Harvey et al. 1993	Canterbury, New Zealand	pasture	biocontrol	na		X
Harvey et al. 1998	Canterbury, New Zealand	pasture	biocontrol	na	X	X
Hodgson 1958	Montana, United States	pasture, alfalfa	herbicide integrated	4		X

			mowing	na		X
Hurrell and Bourdot 1996	Canterbury, New Zealand	pasture	biocontrol	na		X
			mowing	na	X	
			non-herbicide integrated	na	X	
Hurrell and Bourdot 2001	Canterbury, New Zealand	pasture	biocontrol	na	X	
Krueger-Mangold 2002 et al. *	Montana, United States	natural area	herbicide	9		X
McKay 1959	Idaho, United States	alfalfa	competition	na		X
			herbicide integrated	4		X
Meeklah and Mitchell 1984	Otago, New Zealand	pasture	herbicide	4	X	X
			herbicide integrated	4	X	
			mowing	na	X	
Melichar and Stafford 1989	Iowa, Kentucky, and Indiana, United States	roadside	herbicide	4	X	

Mesbah and Miller 2005 *	Wyoming, United States	alfalfa	herbicide	2, 4, 6, mix	X	
Peterson and Parochetti 1978	Maryland, United States	range	herbicide	4	X	
Samuel and Lym 2008	North Dakota, United States	range	herbicide	4	X	X
Sebastian et al. 1992	Colorado, United States	range	herbicide	2, mix		X
Thrasher et al. 1963	Montana, United States	range	fertilizer	na	X	
			water manipulation	na	X	
			non-herbicide integrated	na	X	
Tipping 2001	Maryland, United States	range	herbicide	5	X	
Travnicek et al. 2005	North Dakota, United States	range	burn	na	X	
			herbicide	4	X	
			herbicide integrated	4	X	
Vantoor 1994	Southland, New Zealand	pasture	herbicide	9		X

Wedryk and Cardina 2012	Ohio, United States	pasture	competition	na	X	
Whitson and Ferrell 1986	Wyoming, United States	range	herbicide	4		X
Wilson and Kachman 1999	Nebraska, United States	pasture	competition	na	X	
			herbicide integrated	4, 9	X	
			non-herbicide integrated	na	X	
Wilson and Michiels 2003	Nebraska, United States	range	herbicide	4	X	
Wilson et al. 2006	Nebraska, United States	pasture	herbicide	4	X	