A systematic review of Canada thistle (*Cirsium arvense*) control and management studies in organic and diversified cropping systems for the Northern Great Plains region

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Executive Summary

Management of perennial weeds is one of the greatest challenges to the long-term sustainability of organic agriculture in the Northern Great Plains (NGP). Canada thistle (*Cirsium arvense*) is a particularly problematic perennial weed because it reproduces not only by seed, but also through an extensive underground root system that is difficult to target using organic methods. Researchers have explored many different approaches to manage Canada thistle in organic systems, but no clear solutions or recommendations exist. Most management recommendations focus on depleting carbohydrate reserves in its extensive root system, and include methods such as mechanical and cultural techniques as well as grazing management and biological control. Despite the variety of potential management techniques, more research on approaches to manage Canada thistle in organic systems is needed. We systematically reviewed previous research to determine which aspects of non-chemical Canada thistle management warrant further study and to highlight best management practices for its control.

Our literature search revealed that little research has been conducted about non-chemical management of Canada thistle in the NGP. Only 11 papers out of 74 in our analysis were conducted in this region. We included research from around the globe in our analysis, and we were able to determine which research areas appear promising and to highlight management practices that may be useful for grower in our region. Our main research findings from the systematic review were:

- Overall, integrated management, where two or more control methods are combined to manage Canada thistle, holds the most promise. For annual cropping systems, integrated management of Canada thistle in the NGP using competitive vegetation combined with

other management techniques such as tillage would be a beneficial area for future research.

- Dense stands of annual forage crops were effective in suppressing Canada thistle. However, none of the studies in our analysis were conducted in the NGP, and the success of this method in other areas warrants investigation in our region.
- Repeated soil cultivation can decrease Canada thistle abundance. However, only one study in our analysis was conducted in the NGP. Due to the risk of erosion, research about the best methods of mechanical control of Canada thistle for the NGP which balance soil health and weed abundance would be beneficial.
- Shading with plastic mesh material reduced Canada thistle biomass to the greatest degree of any method we researched for this analysis and it may be a potential management technique to consider for small areas. Similarly, solarization caused a large reduction in Canada thistle abundance, but it was only implemented in one study where the effects were only recorded over a one year period. It may be beneficial to investigate longer-term effects of these management techniques in the NGP.
- In our analysis of perennial systems few methods decreased Canada thistle abundance. Overall, establishing a stand of competitive perennial vegetation emerged as a good technique for decreasing Canada thistle abundance in habitats such as hay fields and pastures.
- Modifying grazing strategies has been effective for reducing Canada thistle abundance in other areas of the world, but information about grazing management to reduce Canada thistle abundance in the NGP is lacking.

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Introduction

Management of perennial weeds is one of the greatest challenges to the long-term sustainability of organic agriculture in the Northern Great Plains (NGP), and identifying methods of reducing the spread and impact of Canada thistle is a priority for organic grain and vegetable growers (Grisak, 2012; OAEC, 2013). Canada thistle is a particularly problematic perennial weed because it reproduces not only by seed, but also through an extensive underground root system that is difficult to target using organic methods (Nadeau and Vanden Born, 1989). The need for approaches to successfully manage Canada thistle is growing as current management approaches are not effective and producers need information regarding more promising management strategies. In fact, in a survey of organic growers conducted by the OAEC, 75% of respondents categorized Canada thistle as being either “Hard” or “Impossible” to control, and producers identified it as one of the top two weed issues where research is most needed (OAEC, 2013).

Researchers have explored many different approaches to manage Canada thistle in organic systems, but no clear solutions or recommendations exist. Most management recommendations focus on depleting carbohydrate reserves in its extensive root system. One commonly recommended method of controlling this weed is repeated tillage (i.e. Hodgson, 1958), but relying solely on repeated tillage in the relatively dry ecosystems of the NGP is not sustainable due to erosion and soil moisture concerns, as well as cost. However, the integration of tillage with sowing of a competitive crop may provide some Canada thistle control (i.e. Lukashyk et al, 2008). Cultural practices such as cultivation of competitive summer annual cover crops may suppress Canada thistle because peak growth occurs when Canada thistle root reserves are low (Bicksler and Masiunas, 2009). Potential approaches to managing Canada thistle in organic systems also include targeted grazing and biological control. Despite the variety of potential management techniques, more research on approaches to manage Canada thistle in organic systems is needed.

The first objective of this project was to quantify and compare the effectiveness of different management practices carried out to manage Canada thistle in organic and diversified cropping systems. We also sought to determine which aspects of Canada thistle management require further study. Thoroughly reviewing and quantitatively assessing the information available about managing this species will not only help the OAEC determine what aspects of

Canada thistle management warrant further study, but will also highlight current best management practices for its control and provide ideas to improve its management.

Methods

Literature Search

For the initial literature search, our intent was to be inclusive. We searched the Web of Science® (1864-2015) and Agricola® (1970-2015) databases for the terms "*Cirsium arvense*," “Carduus arvensis,” "Canada thistle," "creeping thistle," and "Californian thistle,” and “field thistle.” We limited our search to papers written in English.

Systematic Review

Studies were included in the next step of the analysis if non-chemical management techniques were applied to Canada thistle in a field setting (i.e. greenhouse studies were not included), regardless of the agronomic systems or geographic areas where the study was conducted. Included papers also had measurements for a change in abundance of Canada thistle in response to a control method. These measurements included percent cover, density, biomass, and percent control.

Quantitative Analysis

Our original objective, as stated in our proposal to the OAEC, was to conduct a formal meta-analysis of Canada thistle management. However, most of the articles we found did not report measures of variability such as standard error or standard deviation, and these measurements are needed to perform required steps of formal meta-analysis. Variability is the extent to which data points differ from one another. For example, if a control measure is tested on three different fields, variability would be the extent to which results from each field are different than the average across all three fields. To summarize information from all Canada thistle studies that met our search criteria, *we instead conducted a quantitative summary analysis rather than a formal meta-analysis* (Pullin and Stewart 2006). This approach requires that we have means (i.e. averages), but not estimates of variability. In a true meta-analysis, we would use the measures of variability to weight mean Canada thistle responses to treatments, whereas in this report we use unweighted means. Using this approach, we may misrepresent true means if they have high variability, but we considered this a small risk compared with biasing our analysis by using only the relatively few articles available that did report measures of variation.

To begin the analysis, we first identified fifteen treatment categories used in the selected studies to manage Canada thistle (Table 1). We also separated studies conducted in annual systems (row crop, fallow, etc.) from those conducted in perennial systems (pasture, hay, natural areas, etc.). In order to compare these studies to one another, we first had to take the reported data and calculate an effect size for each one. An effect size is an index that measures the size of a treatment effect by comparing a treated group to a non-treated group. We used the response ratio (RR) as an effect size (Goldberg et al 1999), and calculated it for each Canada thistle measurement as:

RR = natural log(mean for an experimental group/mean for non-treated group)

We then calculated an average effect size for each treatment category in Table 1. We also calculated 95% confidence intervals for each of these averages as: mean ± $1.96(\sigma/\sqrt{n})$. Here, σ is standard deviation and n is the sample size. *Negative effect sizes indicate a reduction in Canada thistle abundance, while positive effect sizes indicate an increase*. We considered effect sizes to be different from zero if their confidence intervals did not overlap zero and effect sizes were different from one another if confidence intervals did not overlap (Gurevitch et al 1992).

Table 1. Treatment categories used to conduct a quantitative analysis of non-chemical Canada thistle management tactics.

Management Categories	*Description*
Biocontrol	Biological control with insects or pathogens
Burning	Impact of prescribed fire on Canada thistle populations
Competition	Any method attempting to increase crop competitive ability including ridge sowing, manipulating row spacing or planting dates, revegetation, and trials with competitive species or cultivars
Crop Diversification	Adding cover crops or increased crop rotation to a cropping system
Grazing	Using animals to graze Canada thistle
Integrated	Any combination of two or more control methods.
Irrigation	Changing water availability
Mechanical	Any mechanical control method including hand or mechanical hoeing, hand weeding, or cultivation
Mowing	Mowing the site
Mulch	Use of either plastic or organic mulches
Reduced Tillage	Impact of reduced tillage intensity on Canada thistle control
Shading	Reduction in light availability using shade cloth
Soil Amendments	Application of amendments such as manure or fertilizer
Solarization	Heating the soil by using dark or translucent plastics
Wounding	Injuring plants by crushing or trampling

Results and Discussion

Literature Search

Our initial literature search yielded 1775 papers. We then screened titles and abstracts of those studies and performed a full-text review of 364 papers. As a result of the screening, we collected 73 papers that met the criteria stated above, and we used these papers for our analysis (Fig. 1). Of these, 30 studies were conducted in annual systems, 39 were conducted in perennial systems, and four were conducted in both annual and perennial systems. The appendices include two tables outlining the specifics of each paper used in the analysis including authors, date of publication, duration of study, and average effect sizes for each Canada thistle management technique used in each paper. Appendix 1 includes studies focused on annual systems, while Appendix 2 lists papers about perennial systems.

A few key observations can be drawn from the literature review we conducted during this search and filtering process (Appendix 1 and 2). Most importantly, little research has been done on non-chemical Canada thistle management in the NGP, defined as the area bordered by Nebraska on the south, the western boundary of Montana, the eastern boundaries of North and South Dakota, and the northern edge of cultivation in western Canada (Blade et al 2002). Specifically, only 11 papers out of 74 in the analysis were conducted in this region.

Quantitative Analysis; Annual Systems

Four broad groups of control method effectiveness were delineated in annual systems, based on the results of the analysis (Fig. 2). Integrated management, shading, and solarization caused the largest decrease in Canada thistle abundance, and thus can be considered the most effective methods. The next best group of Canada thistle control methods included biocontrol, crop diversification, mechanical control, and mowing. Competition and soil amendments did not make a difference in Canada thistle abundance, and reduced tillage increased Canada thistle abundance. We will discuss the methods that decreased Canada thistle abundance below.

Integrated management: We defined integrated management as when two or more methods were used in conjunction to manage a population of Canada thistle. In our analysis of annual systems, five studies investigated integrated Canada thistle management, and all of these methods included sowing competitive vegetation combined with another management technique. The technique that decreased Canada thistle abundance most effectively was identified in a three year study that implemented one season of repeated tillage followed by one season of annual grass/legume forage crops followed by seeding spring wheat (Lukaskyk et al. 2008). Another effective method presented by Lukashyk et al. (2008) was establishing a perennial stand of ryegrass and clover that was repeatedly mown for two years, then plowed once and seeded to spring wheat. Both of these methods reduced Canada thistle abundance by 99%. One study that covered integrated methods in the NGP was conducted by Hodgson (1950), but this study investigated sowing spring wheat and using fertilizer, and this method actually increased Canada thistle abundance. In summary, management of Canada thistle using competitive vegetation combined with other management techniques such as tillage may be a beneficial area for future research.

Shading: This approach to manage Canada thistle caused a substantial decrease in abundance, but it was only investigated in one study. Specifically, Hettwer et al (2012) used plastic shade nets to decrease light transmission by 15% in May, and by 5% in June and July. The intent of the study was to mimic the effect of wheat shading Canada thistle, rather than to study the effect of shading itself. However, this method reduced Canada thistle biomass by almost 100%, or to the greatest degree of any method we researched for this analysis, and it may be a potential management technique to consider for small areas in the future. It also further highlights the potential importance of crop competition as an approach to decrease Canada thistle abundance.

Solarization: In the only study where solarization was assessed as a method to manage Canada thistle, it caused a 98% reduction in Canada thistle abundance. Candido et al (2011) used three different plastic films to solarize plots in a fallow field. The field was then planted to lettuce. Based on the results of this study, solarization is a promising method of Canada thistle control. However, the study was only conducted over a one year period. It would be beneficial to investigate longer-term effects of this management technique.

Biocontrol: The seven studies that investigated biocontrol used a variety of agents including both pathogens and insects like the tortoise beetle *Cassida rubiginosa*, but caused a moderate decrease in Canada thistle abundance. In the study that had the largest decrease in Canada thistle abundance in this category, Tipping (1993) infected Canada thistle shoots with the pathogen *Puccinua punctiformis* and this treatment resulted in 85% mortality measured over one season. Brosten et al (1986) achieved an 80% decrease after two years using the pathogen *Sclerotinia sclerotiorum* incorporated in the soil. These two studies were both carried out in fallow fields.

Crop Diversification: We identified seven studies that evaluated the impact of crop diversification on Canada thistle. Of these, one study implemented crop rotation, and had the largest decrease in Canada thistle abundance. Specifically, McKay (1959) implemented a rotation of a two year stand of an alfalfa-grass mix followed by potatoes and achieved a 96% reduction in Canada thistle. He concluded that thick stands of forage crops were “highly effective” in suppressing and controlling this species. The study that had the next largest decrease in Canada thistle abundance implemented a late sowing of sorghum, sudangrass, sunflower, and soybean (Wedryk and Cardina, 2012). This method resulted in a 92% decrease in Canada thistle abundance after two years. None of the crop diversification studies were conducted in the NGP.

Mechanical Control: In annual systems, our analysis had the most studies in the mechanical control category. The study that had by far the greatest reduction in Canada thistle abundance was implemented in Montana by Hodgson (1970), who investigated the effect of repeated cultivation on Canada thistle that originated from various areas. In this experiment, fallow ground was cultivated using duckfoot sweeps every 21 days throughout the growing season, and this method led to a 99% reduction in Canada thistle abundance after two years. This study took place near Bozeman, MT. Many other studies reported Canada thistle reductions with one cultivation per season. For example, Pekrun and Claupein (2004) implemented stubble tillage techniques using either a rototiller or shallow plow, and both of these methods decreased Canada thistle abundance by 90% after five years. Due to the increased risk of soil erosion associated with cultivation, research about the best methods of mechanical control of Canada thistle for the NGP which balance soil health and weed abundance would be beneficial.

Mowing: This approach was investigated as part of three studies in our analysis of annual systems, and it was moderately effective in controlling Canada thistle. In each case, mowing was conducted on cover crops. The most effective mowing treatment was growing a diverse green manure stand including grasses and legume and non-legume forbs and cutting it once during the growing season (Thomsen et al 2011). This method led to a 68% decrease in Canada thistle abundance after one year. None of the experiments that investigated mowing were conducted in the NGP.

Quantitative Analysis: Perennial Systems

The studies we used in our quantitative summary analysis can be broadly broken into three groups of Canada thistle management strategies (Fig. 3): management tactics that either decreased Canada thistle, had no effect on its abundance, or increased it. Biocontrol, competition, grazing, and integrated management all decreased Canada thistle abundance. Irrigation, mowing, mulching, and soil amendments did not impact Canada thistle abundance. Finally, prescribed burning increased Canada thistle abundance. We will discuss the categories that decreased Canada thistle abundance below.

Biocontrol: Of the ten studies about biological control of Canada thistle in perennial systems, most used pathogens such as *Puccinia punctiformis* and *Sclerotinia sclerotiorum,* and were conducted in pastures. Only one study in our analysis implemented biological control with insects. Eight of these ten studies were conducted in New Zealand, so they may have limited applicability to the NGP. Three of the four most effective methods were from two studies by Bourdot et al (1993 and 1995). They used pathogen *S. sclerotiorum* to control Canada thistle in perennial ryegrass/clover pastures in New Zealand, and reduced its abundance by up to 92% after one year. One biocontrol study by Brosten et al (1986) was implemented in pasture settings in Havre and Benchland, Montana. The authors applied *S. sclerotiorum* and attained 80% and 44% Canada thistle mortality with their high rate of application after two years. Biological control with pathogens in perennial systems has been receiving interest from researchers in Colorado in recent years as well, where studies are currently being conducted on *P. punctiformis*.

Competition: There were nine studies in this category of our analysis, and one was conducted in Montana. Most studies in this category investigated the effect on Canada thistle abundance of sowing perennial vegetation such as pasture grasses. The top three most effective methods in this category all involved sowing a mix of perennial grasses and forbs (Ang et al 1994a; Pekrun and Claupein, 2004; West et al 1997). One study investigated the effect of high seed mix diversity and another the effect of alfalfa row spacing, but these methods did not have a large impact on Canada thistle (Bezemer et al, 2004; Celebi et al, 2010). In the study conducted in Montana, Thrasher et al (1963) tested if five different perennial grass species suppressed Canada thistle. Troy Kentucky bluegrass and Russian wildrye were the species that decreased Canada thistle abundance most effectively in their study, reducing it by 73% and 69%, respectively after three years. Further research into perennial seed mixes and species that effectively suppress Canada thistle in the NGP are warranted.

Grazing: Grazing was only represented by three studies in our analysis, with two in New Zealand and one in the NGP (Alberta, Canada). The studies in this category mostly investigated reducing Canada thistle abundance by increasing grazing intensity. The most effective approaches were implemented by Hartley et al (1984), who tried different levels of rotational and set-stock type grazing with sheep in New Zealand. They achieved a 95% decrease in Canada thistle abundance after three years with hard rotational grazing in the spring followed by the same regime in the fall. De Buijn and Bork (2006) implemented a short duration, rotational cattle grazing regime in Alberta, which did reduce Canada thistle in comparison to their conventional method of season-long grazing. However, it was not as effective as the grazing regime used in New Zealand, reducing Canada thistle abundance by 47% after three years. Modifying grazing strategies has been effective in other areas of the world, but information about grazing management to reduce Canada thistle abundance in the NGP is lacking. This topic would be a good area for further research.

Integrated Management: The two papers with the most effective integrated management approach to Canada thistle management were conducted in Montana and Idaho. In Montana, Hodgson (1958) sowed an alfalfa stand that was then mowed for hay for four years. This treatment resulted in a 99% decrease in Canada thistle abundance. In Idaho, McKay (1959) sowed an alfalfa-grass stand that was mowed for hay for five years. His treatment was similar in effectiveness to that of Hodgson (1958). Another effective method implemented in New Zealand was mowing combined with high intensity grazing (Mitchell and Abernathy, 1995), which led to a 90% reduction in Canada thistle abundance after two years. Sowing a competitive stand of vegetation and haying it over multiple years may be an effective method of Canada thistle suppression, and it is worth conducting further research or on-farm trials to determine the best ways to implement this control strategy.

Overall conclusions

In annual cropping systems, integrated management, shading, and solarization caused the largest decrease in Canada thistle abundance, and thus were the most effective methods. The next best group of Canada thistle control methods included biocontrol, crop diversification, mechanical control, and mowing. Based on our analysis, the methods that decreased Canada thistle abundance in perennial systems were biocontrol, competition, grazing, and integrated management. In general, it is interesting that so few methods decreased Canada thistle abundance in our analysis of perennial habitats as most treatment categories showed no detectable effect on Canada thistle. Overall, establishing a stand of competitive perennial vegetation emerged as a good technique for decreasing Canada thistle abundance.

Recommendations for Future Research

Annual Systems:

- Integrated management of Canada thistle in the NGP using competitive vegetation combined with other management techniques such as tillage would be a beneficial area for future research.
- Thick stands of annual forage crops were effective in suppressing Canada thistle. However, none of the studies in our analysis were conducted in the NGP, and the success of this method in other areas warrants investigation in our region.
- It is well-established in previous research that repeated soil cultivation can generally decrease Canada thistle abundance. However, only one study in our analysis was conducted in the NGP. Due to the risk of erosion, research about the best methods of mechanical control of Canada thistle for the NGP which balance soil health and weed abundance would be beneficial.
- Shading with plastic mesh material reduced Canada thistle biomass to the greatest degree of any method we researched for this analysis and it may be a potential management technique to consider for small areas in the future.
- Solarization caused a large reduction in Canada thistle abundance, but it was only implemented in one study where the effects were only recorded over a one year period. It would be beneficial to investigate longer-term effects of this management technique in the NGP.

Perennial Systems:

- For perennial systems, sowing a competitive stand of vegetation and haying it for a period of several years may be an effective method of Canada thistle suppression, and it is worth conducting further research or on-farm trials to determine the best ways to implement this control strategy.
- Further research into perennial seed mixes and species that effectively suppress Canada thistle outside of hayfield habitats in the NGP are also warranted, as establishing a stand of competitive perennial vegetation has been proven to decrease Canada thistle abundance both in the NGP and in other areas of the world.
- Modifying grazing strategies has been proven to be effective in other areas of the world, but information about grazing management to reduce Canada thistle abundance in the NGP is lacking. This topic would be a suitable area for further research.

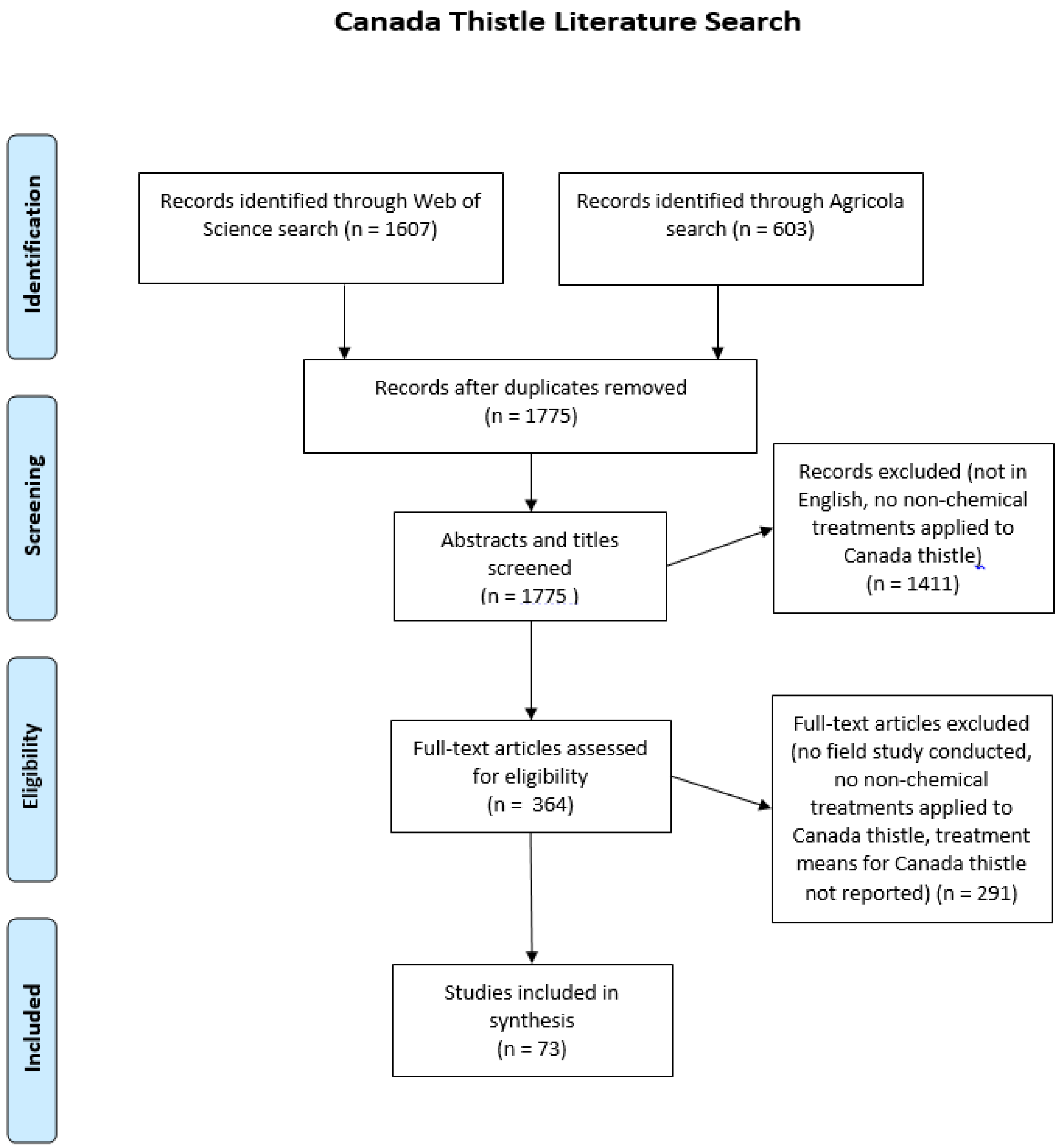

Figure 1. Flow chart showing the steps taken during the literature screening portion of the systematic review of non-chemical Canada thistle control. In each box, n is the number of records present in that step.

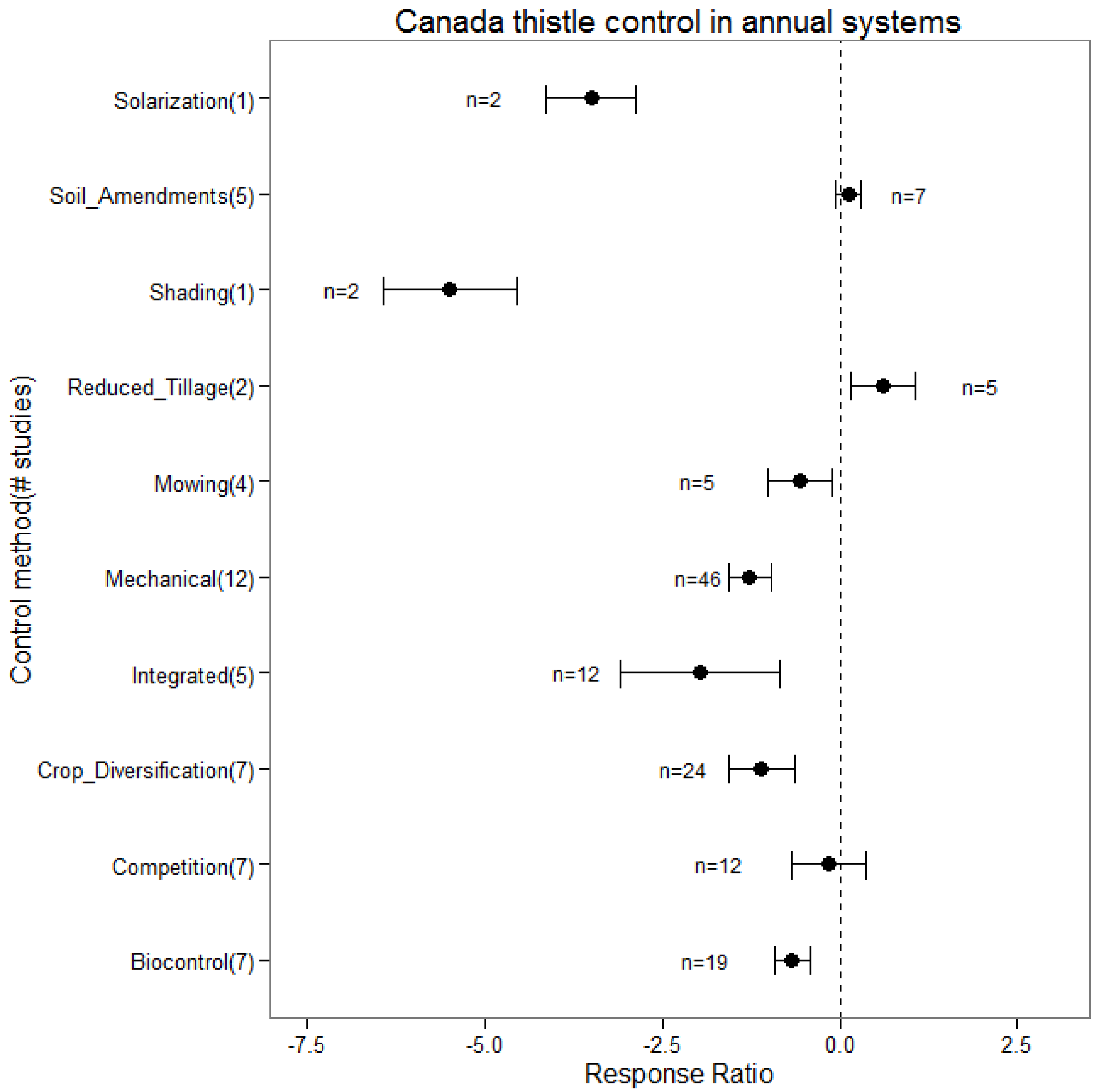

Figure 2. Mean effect sizes, or response ratios (points), and 95% confidence intervals (lines and brackets) for non-chemical Canada thistle control in annual cropping systems. *More negative means correspond with a greater decrease in Canada thistle abundance*. Control methods decrease Canada thistle abundance if the confidence intervals do not cross zero (dotted line). Methods are different from one another if confidence intervals do not overlap. For each method, n is the number of observations that was used to calculate the mean, and the number in parentheses after control methods on the y-axis is the number of studies that covers each method.

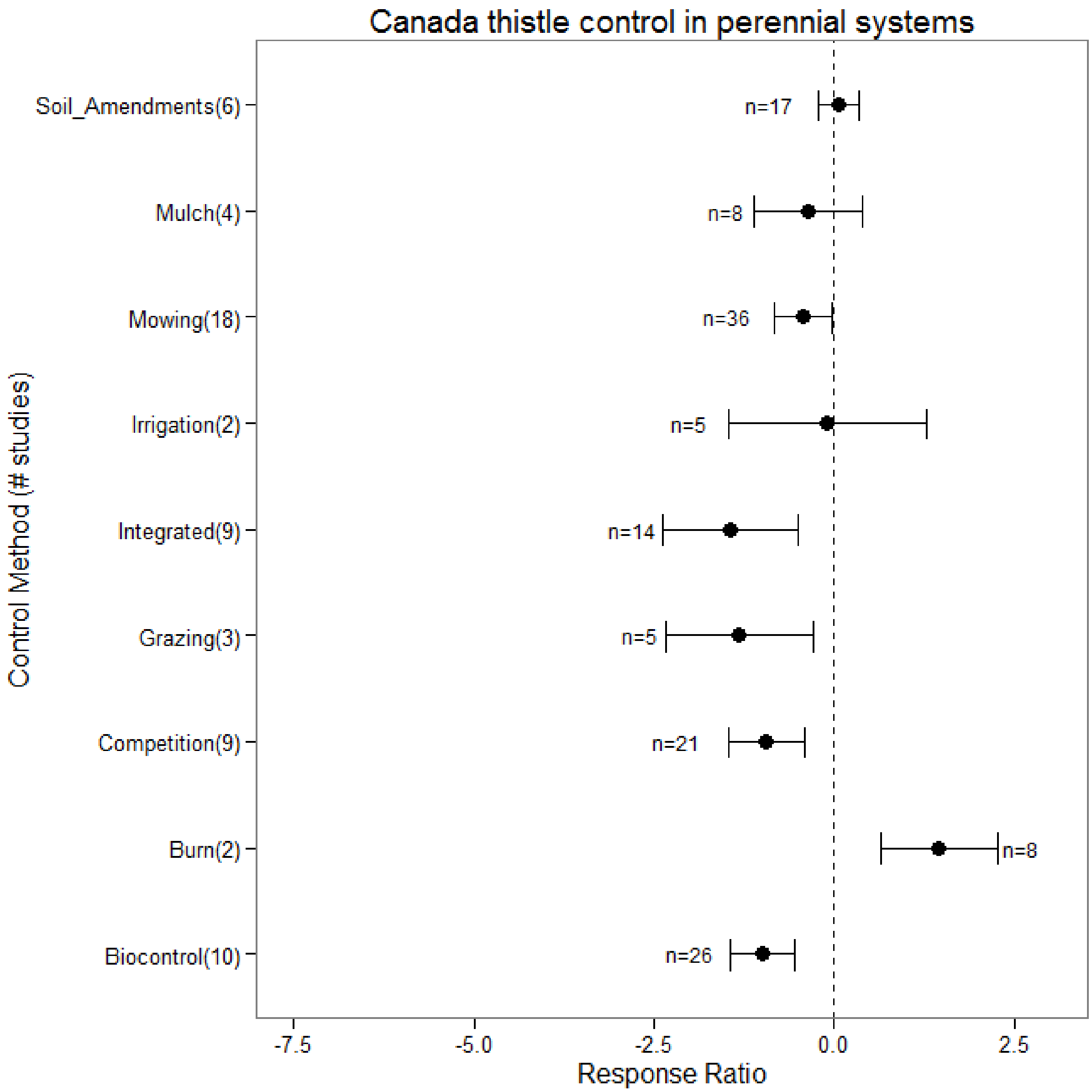

Figure 3. Mean effect sizes, or response ratios (points) and 95% confidence intervals (lines and brackets) for non-chemical Canada thistle control in perennial systems. *More negative means correspond with a greater decrease in Canada thistle abundance*. Control methods decrease Canada thistle abundance if the confidence intervals do not cross zero (dotted line). Methods are different from one another if confidence intervals do not overlap. For each method, n is the number of observations that was used to calculate the mean, and the number in parentheses after control methods on the y-axis is the number of studies that covers each method.

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Appendix 1: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in annual systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
AAMISEPP 1983	Unknown	4 years	Spring cereal crops	Stubble tillage	Mechanical	-0.598
ASADI ET AL 2013	Mashad, Iran	2 years	Fallow	*Cassida rubiginosa* beetle	Biocontrol	-1.462
			Wheat	*Cassida rubiginosa* beetle	Biocontrol	-1.183
BACHER AND SCHWAB 2000	Bern, Switzerland	1 year	Fallow	*Cassida rubiginosa* beetle	Biocontrol	-0.115
				Seeded herbs as competitive vegetation	Competition	-0.515
				Seeding and *C. rubiginosa*	Integrated	-0.515
BICKSLER AND MAISUNAS 2009	Champaign, IL	2 years	Cover crops	Cover crops (buckwheat, sudangrass-cowpea mix)	Crop Diversification	-1.656
				Cover crops mown 2 times	Mowing	-0.811
BRANDSAETER ET AL 2011	Kapp, Norway	2 years	Green manure, spring barley, oats with peas	Cultivation	Mechanical	-1.320
BRANDSAETER ET AL 2012	As, Norway	4 years	Spring oats	Cover crops (red clover)	Crop Diversification	0.239
				Cultivation (various including rotary tillage, plough, harrow)	Mechanical	-1.638
				Mowing	Mowing	0.110
BROSTEN ET AL 1986	Bozeman, MT	2 years	Fallow	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.792

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 1: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in annual systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
CANDIDO ET AL 2011	Metaponto, Italy	1 year	Fallow followed by lettuce	Solarization with various plastics	Solarization	-3.501
COUKELL 1966	Manitoba, Canada	2 years	Oats and summer fallow	Crop competition (oats)	Competition	-0.261
				Intensive cultivation- rototilled 5 to 6 times per year	Mechanical	-1.897
GRAGLIA ET AL 2006	Slagelse, Denmark	3 years	Spring barley	Hoeing	Mechanical	-1.006
				Hoeing + undersown with red or white clover	Integrated	-1.850
GRONWALD ET AL 2002	Minnesota, United States	2 years	Soybean	*Pseudomonas syringae* pv. *Tagetic* pathogen	Biocontrol	-0.011
GRUBER AND CLAUPEIN 2009	Stuttgart, Germany	2 and 5 years	Rotation including small grains, cover crops, potato	Perennial grass/clover mix sown	Competition	-0.668
				Cultivation (various including chisel plough, rototiller, deep plough)	Mechanical	-0.924
HETTWER ET AL 2002	Germany	1 year	Fallow	Nitrogen fertilizer	Soil Amendments	0.382
				Light intensity reduction	Shading	-5.490
HODGSON 1958	Bozeman, MT	4 years	Spring wheat	Competition with spring wheat	Competition	0.100
				Spring wheat + nitrogen fertilizer	Integrated	0.787
HODGSON 1970	Montana	2 years	Fallow	Intensive cultivation with duckfoot sweeps repeated every 21 days	Mechanical	-5.915

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 1: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in annual systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
JASINSKAITE ET AL 209	Akademija, Lithuania	1 year	Buckwheat or spring wheat phase of small grain rotation	Two-layer plough	Mechanical	-1.262
JOHNSON ET AL 1996	Not specified	1 year	Maize	*Pseudomonas syringae* pv. *Tagetis* pathogen	Biocontrol	-0.844
KLUTH ET AL 2005	Lower Saxony, Germany	3 years	Fallow	*Puccina punctiformis* and *Phoma destructiva* pathogens	Biocontrol	0.149
KOLO AND FROUD WILLIAMS 1993	Berkshire, England	1 year	Spring barley or fallow	Nitrogen fertilizer	Soil Amendments	-1.028
				Spring barley + nitrogen fertilizer	Integrated	0.094
LEHOCZKY ET AL 2013	Keszthely, Hungary	2 years	Wheat/maize rotation	No-till drill or disc tillage	Reduced Tillage	1.135
LUKASHYK ET AL 2008	Westphalia, Germany	3 years	Spring wheat	Repeated (3x) stubble tillage, annual forage crop, followed by spring wheat	Integrated	-5.655
				Rye-clover pasture repeatedly mown and mulched, followed by spring wheat	Integrated	-5.573
				Rye-clover pasture (repeatedly mown and mulched) followed by annual forage crop, followed by spring wheat	Integrated	-2.661
MCKAY 1959	St. Anthony, ID	5 years	Potato	Rotation of alfalfa/grass mix and potato	Crop Diversification	-3.219
			Spring wheat	Nitrogen fertilizer	Soil Amendments	-0.174

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 1: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in annual systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
MELANDER ET AL 2012	Vestsjalland, Denmark	3 years	Spring barley	Nine cultivation treatments	Mechanical	-1.461
NADEAU ET AL 1990	Edmonton, Alberta	2 years	Fallow	Nitrogen fertilizer	Soil Amendments	0.286
PEKRUN AND CLAUPEIN 2004	Baden-Wurttemberg, Germany	6 years	Rotations of cereals, beans, and potatoes	Stubble tillage: rototiller, shallow plough, or cultivator	Mechanical	-1.228
PILIPAVICUS ET AL 2011	Akademija, Lithuania	3 years	Spring barley	Increased seeding rate	Competition	0.777
RABCEWICZ 1995	Alnarp, Sweden	1 year	Fallow	Cultivation with a ring blade or spring tines	Mechanical	-1.644
REISINGER AND PALMAI 2007	Fejer, Hungary	1 year	Wheat	Seeding date	Competition	1.337
RUSU ET AL 2006	Cluj-Napoca, Romania	4 years	Variety of monocultures: soybean, wheat, corn, potato, rape,	Chisel + rotary harrow or paraplow + rotary harrow	Reduced Tillage	0.263
THOMSEN ET AL 2011	Moystad, Norway	13 months	Fallow	Cover crop mix including vetch, clover, and ryegrass	Crop Diversification	-1.402
				Mowing cover crop	Mowing	-0.640
TIPPING 1993	Maryland, United States	1 year	Fallow	*Puccinia punctiformis* pathogen	Biocontrol	-1.816
WYDRYK AND CARDINA 2012	Wooster, Ohio	2 years	Fallow	Three smother crop mixtures with different planting dates	Crop Diversification	-0.756

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 1: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in annual systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
WYDRYK AND CARDINA 2012A	Wooster, Ohio	2 years	Fallow	Cover crop variety trials used during organic transition	Crop Diversification	-0.593
WYDRYK ET AL 2012	Wooster, Ohio	2 years	Potato or tomato	Organic transition- perennial species or vegetables followed by annual crops	Competition	-0.876
				Organic transition- annual cover crops	Crop Diversification	-1.494
				Organic transition- tilled fallow	Mechanical	-0.155

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 2: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in perennial systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
AMOR AND HARRIS 1977	Victoria, Australia	2 years	Dairy farm-clover/grass mixes	Mowing	Mowing	-0.773
ANG ET AL 1994	Virginia, United States	2 years	Crownvetch/tall fescue pasture	Seeding pasture at 2x recommended rate	Competition	-0.613
ANG ET AL 1994A	Virginia, United States	2 years	Pasture	Seeding tall fescue and crownvetch	Competition	-1.049
ANG ET AL 1995	Virginia, United States	2 years	Pasture	Competition from crownvetch and tall fescue + *Cassida rubiginosa* beetles	Integrated	-1.803
AQUILINA AND CLARKE 1994	Not specified	3 years	Set-aside land	Mown three times a year for two years	Mowing	0.368
BECK AND SEBASTIAN 2000	Colorado, United States	3 years	Subirrigated or upland pasture	Fields mown three times	Mowing	-0.827
BEZEMER ET AL 2004	Colorado, United States	3 years	Pasture	High diversity versus low diversity seed mix	Competition	-0.575
BOURDOT ET AL 1993	Canterbury, New Zealand	1 year	Perennial ryegrass/clover pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-1.280
BOURDOT ET AL 1995	Canterbury, New Zealand	1 year	Perennial ryegrass/clover pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-1.480
BOURDOT ET AL 2004	Canterbury, New Zealand	1 year	Grazed pastures	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.395
BOURDOT ET AL 2006	Templeton, New Zealand	3 years	Perennial ryegrass/clover pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.018
BOURDOT ET AL 2011	Various locations, New Zealand	1 year	Grazed pastures	Mowing during rain to encourage native pathogen infection of Canada thistle	Mowing	-0.404

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 2: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in perennial systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
BRANT ET AL 2004	Prague City, Czech Republic	5 years	Pasture seeded with 4 grasses and 4 legumes	3 cuts per year	Mowing	1.204
				2 cuts and mulchings per year	Mulching	2.058
BROSTEN ET AL 1986	Bozeman, MT	2 years	Pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.889
CELEBI ET AL 2010	Van, Turkey	3 years	Alfalfa	Decreased alfalfa row spacing at planting	Competition	-0.421
CLEMENTS ET AL 2012	Southampton, United Kingdom	1 year	Pasture	Manure slurry or digestate fertilizer	Soil Amendments	-0.684
CRIPPS ET AL 2010	Delemont, Switzerland	1 year	Grass pasture	*Cassida rubiginosa* beetle	Biocontrol	-0.160
DE BRUIJN AND BORK 2006	Alberta, Canada	3 years	Pasture	Rotational grazing	Grazing	-0.638
DE BRUIJN ET AL 2010	Alberta, Canada	3 years	Pasture	Defoliation by clipping	Mowing	0.995
DE CAUWER ET AL 2006	West Flanders, Belgium	4 years	Perennial field margin	Perennial seed mix	Competition	-1.288
				Mown with removal of biomass	Mowing	-1.758
				Mown without removing herbage	Mulching	-0.926
DINKINS 2005	Nebraska, United States	2 years	Vegetation plots near reservoir	Clipping under open and closed vegetation canopy	Mowing	0.502
EDWARDS ET AL 2000	Berkshire, United Kingdom	2 years	Grassland	Sown with perennial seed mix	Competition	0.081
				Various fertilizers applied	Soil Amendments	0.387

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 2: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in perennial systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
GAISLER ET AL 2006	Liberec, Czech Republic	6 years	Pasture	Mowing with biomass removed	Mowing	-2.904
				Mowing with biomass used as mulch	Mulching	-1.189
GAISLER ET AL 2008	Liberec, Czech Republic	8 years	Pasture	Mowing with biomass removed	Mowing	-2.913
				Mowing with biomass used as mulch	Mulching	-0.564
GREKUL ET AL 2007	Alberta, Canada	3 years	Pasture	Mowing once	Mowing	-0.271
				Fertilizer	Soil Amendments	-0.046
				Mowing once and fertilizer	Integrated	0.109
HARTLEY AND JAMES 1979	Hamilton and Bulls, New Zealand	3 years	Pasture	Hand-cutting thistles 4 times/years	Mowing	-0.941
HARTLEY ET AL 1984	Palmerston North, New Zealand	2 years	Pasture	Rotational grazing regimes	Grazing	-1.581
				Rotational grazing combined with topping	Integrated	-0.701
HAY AND OUELLETTE 1959	Quebec, Canada	3 years	Pasture	Fertilizer application	Soil Amendments	0.000
HODGSON 1958	Bozeman, MT	4 years	Alfalfa	Alfalfa and mowing	Integrated	-4.956
HOGENBIRK AND WEIN 1991	Alberta, Canada	2 years	Wetland	Prescribed burn	Burn	0.263
				Decreased water availability	Irrigation	1.282

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 2: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in perennial systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
HURRELL AND BOURDOT 1996	Canterbury, New Zealand	2 years	Pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.202
				Mowing 3 times each summer	Mowing	-1.893
				Sclerotinia sclerotiorum and mowing	Integrated	-2.488
HURRELL AND BOURDOT 2001	Canterbury, New Zealand	2 years	Pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.487
HURRELL ET AL 2001	Various locations, New Zealand	2 and 3 years	Pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.602
KOCOURKOVA ET AL 2008	Prague, Czech Republic	4 years	Grass pasture	Nitrogen fertilizer	Soil Amendments	0.528
				Pasture cut once and mulched	Mulching	-0.468
				Seeded grasses + fertilizer	Integrated	0.350
MCKAY 1959	St. Anthony, Idaho	5 years	Pasture	Alfalfa and grass seeded and mown for hay	Integrated	-4.601
MITCHELL AND ABERNATHY 1995	Southland, New Zealand	2 years	Pasture	Hard grazing	Grazing	-0.357
				Topping to height of 5 to 7.5 cm	Mowing	-2.124
				Grazing and topping	Integrated	-2.303
MITCHELL AND DAVIS 1996	New Zealand	1 year	Grass/clover pasture	*Sclerotinia sclerotiorum* pathogen	Biocontrol	-0.818
				Topped at pre-bolting twice a year	Mowing	-0.618

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.

Appendix 2: Studies used in systematic review and quantitative analysis of non-chemical Canada thistle control in perennial systems.

CITATION	STUDY LOCATION(S)	STUDY DURATION	CROPPING SYSTEM/PHASE	INTERVENTION UNDER INVESTIGATION	INTERVENTION CATEGORY	MEAN EFFECT SIZE
PEKRUN AND CLAUPEIN 2004	Baden-Wurttemberg, Germany	6 years	Perennial clover grass mix	Perennial clover/grass mix planted	Competition	-5.799
PYWELL ET AL 2010	Buckinghamshire and Powys, England	6 years	Species-poor pasture	Hay species planted	Competition	0.053
				Pastures cut for hay	Mowing	-0.127
RENZ AND SCHMIDT 2012	Arlington and Franbrook, Wisconsin	2 years	Grass pasture	Clipped to various heights	Mowing	0.962
SCHREIBER 1967	Lafayette, Indiana	4 years	Alfalfa	Mown	Mowing	-2.575
THOMPSON AND SHAY 1989	Manitoba, Canada	1 year	Marsh	Prescribed burn	Burn	1.857
THRASHER ET AL 1963	Montana, location not specified	3 years	Grass pasture	Various perennial grasses seeded	Competition	-0.864
				Irrigation to maintain near field capacity	Irrigation	-1.016
				Nitrogen fertilizer	Soil Amendments	0.288
				Irrigation + fertilizer	Integrated	-1.099
WATSON AND KEOGH 1981	Canada, location not specified	1 year	Roadside and pasture	*Puccinia punctiformis* pathogen	Biocontrol	-3.508
WEST ET AL 1997	Various locations, England	4 years	Field boundary strips	Various perennial seeding treatments	Competition	-0.810

*Citations in italics are studies that were conducted in both annual and perennial systems and are included in both Appendix 1 and 2.