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A meta-analysis of field bindweed (*Convolvulus arvensis* L.) and Canada thistle (*Cirsium arvense* L.) management in organic agricultural systems

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ABSTRACT

Organic farming has become a major agricultural and economic sector, and weed management is one of the primary challenges facing the industry. Of particular concern are rhizomatous perennial weeds such as field bindweed (*Convolvulus arvensis* L.) and Canada thistle [*Cirsium arvense* (L.) Scop.] which are highly competitive and not easily controlled in organic systems. We conducted meta-analyses of the existing literature to 1) identify promising management approaches for these weeds in the absence of synthetic herbicides and 2) determine which aspects of field bindweed and Canada thistle management warrant further study. Mechanical control (i.e. plowing, cultivation, hoeing) was the most studied management category in annual cropping systems, accounting for 40% of data extracted, but did not outperform most of the other management actions overall, possibly due to the variability in specific methodology (i.e. timing, frequency, depth, implement). In annual systems, integrated management, or the combination of two or more control methods, emerged as the management technique that caused the greatest decrease in abundance and survival for field bindweed. We identified several additional management techniques that decreased field bindweed and/or Canada thistle in both annual and perennial systems including biocontrol, mowing, grazing, crop diversification, solarization, shading, flaming, and crop competition. However, organic producers continue to struggle with these species. This discrepancy may originate from the fact that most of the studies we evaluated reported impacts over short time spans, with 53% being conducted for a period of one to two years, and only 9% conducted for five or more years. Further, only 16% of field bindweed and 26% of Canada thistle studies reported measures of variability. Longer-term research focused on sustainable perennial weed management systems is needed in addition to research about short-term interventions.

1. Introduction

With $43 billion in annual sales, consumer demand for organic products showing yearly double-digit growth, and nationwide availability in nearly 20,000 natural food stores and in three out of four major retailers (United States Department of Agriculture – Economic Research Service, 2016), organic production has become a major agricultural and economic sector in the United States. Weed control has been identified as one of the primary challenges in organic production (i.e. Tautges et al., 2016). The management of annual weeds in agricultural settings has improved with ecologically-based tactics such as the development of competitive crop genotypes to enhance weed suppression, the integration of multiple management tactics, and the tailoring of management strategies to the temporal and spatial variability of weed populations (Liebman et al., 2016). Yet, organic producers continue to struggle to manage perennial rhizomatous weeds. For example, in recent surveys administered to both agricultural stakeholders and academic researchers, perennial rhizomatous weeds such as field bindweed (*Convolvulus arvensis* L.) and Canada thistle [*Cirsium arvense* (L.) Scop] were specifically acknowledged as obstacles to organic production (OAEC, 2013a, 2013b; Tautges et al., 2016). These species threaten the economic and environmental sustainability of organic enterprises, and developing methods to reduce their spread and impact has been identified as a research priority by organic grain and vegetable growers as well as researchers (DeDecker et al., 2014; Tautges et al., 2016).

Perennial rhizomatous weeds have been difficult to manage in agronomic systems since prehistoric times (Hakansson, 2003a) and were of major concern in Great Plains cropping systems prior to the introduction of synthetic herbicides (i.e. Blankenship, 1901). While these species can be managed with synthetic herbicides, the recent expansion of organic agriculture (United States Department of

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Agriculture – Economic Research Service, 2016) has resulted in a concomitant increase in impact and management concerns related to these species. A main reason for the difficulty in managing perennial weeds in organic systems resides in their biological characteristics. The extensive and persistent underground root system of many perennial species is extremely difficult to manage using organic methods as their carbohydrate reserves provide them with the ability to resist many management techniques used in these types of systems (e.g. regrow after tillage or grow through mulch) and a competitive advantage over crops or other desired vegetation (Bakke et al., 1939; Mohler, 2001b; Nadeau and Vanden Born, 1990). In established stands, the portion of the roots used for carbohydrate storage occurs below soil horizons impacted by tillage, meaning that successful management of these types of species by organic methods requires depletion of these deep root reserves (Mohler, 2001b).

Researchers and organic producers have explored approaches to manage field bindweed and Canada thistle without synthetic herbicides over many decades, but there is no current consensus on best management practices. Historically, the most commonly recommended method for achieving control of these species was through repeated plowing or cultivation applied as often as every one or two weeks, which even led to eradication in some cases (i.e. Hodgson, 1958; Timmons, 1941; Tingey, 1934). While successful in terms of weed control, these studies did not evaluate the economic returns or potential negative environmental consequences of frequent tillage which can result in soil erosion by wind and water, soil moisture storage concerns, and nutrient leaching (Hakansson, 2003b; Parr et al., 1992). However, more recent studies have focused on reducing reliance on tillage by integrating practices that increase crop competitive ability with the goal of depleting carbohydrates stored in the root systems of these weeds (i.e. DallArmellina and Zimdahl, 1988; Lukashyk et al., 2008). Additional approaches to managing these species in organic systems include integrating crop rotation, targeted grazing, solarization, and in some cases biological control (Hakansson, 2003a). To date, no formal study has systematically evaluated the existing literature to assess the effectiveness of these and other methods.

When grappling with difficult issues in agriculture, it can be useful to consult and synthesize findings from previously published literature. One way to accomplish this is through meta-analysis, or the process of statistically merging results of previous research to answer new questions of interest (Gurevitch and Hedges, 2001). The issue of perennial weed management in organic systems is a good fit for meta-analysis as the problem has been identified by agricultural producers and researchers for many years, so there is a substantial amount of information available to synthesize about the topic. A meta-analysis approach has been used to synthesize information in many agronomic topics; Philibert et al. (2012) reported that at the time of their publication five meta-analyses had been conducted targeting pests in agronomic systems. These types of studies are useful for making generalizations about management options, as well as for identifying possible knowledge gaps that exist in the literature (Koricheva and Gurevitch, 2014).

There is a need to systematically evaluate single and integrated approaches to control field bindweed and Canada thistle in the absence of synthetic herbicides. We undertook meta-analyses of the existing literature to 1) identify promising organic management approaches for field bindweed and Canada thistle and 2) determine which aspects of field bindweed and Canada thistle organic management warrant further study.

2. Materials and methods

2.1. Literature search

For the initial literature review, we conducted two searches, one for field bindweed and one for Canada thistle. For the field bindweed search, we searched the Web of Science® (1864–2014) and Agricola® (1970–2014) databases using the Latin binomial, "*Convolvulus arvensis*," and common names, "field bindweed," "creeping jenny," and "perennial morning glory." For the Canada thistle search, we searched the Web of Science® (1864–2014) and Agricola® (1970–2014) databases for the terms "*Cirsium arvense*," "*Carduus arvensis*," "Canada thistle," "creeping thistle," "Californian thistle," and "field thistle." We limited searches to papers written in English. We conducted these searches in November 2014, compared resulting databases, and removed duplicated studies.

Records obtained during the initial literature search were systematically screened following Koricheva and Gurevitch (2014) to determine their suitability for our study based on three main criteria: 1) management techniques that did not include synthetic herbicides were applied to field bindweed or Canada thistle and were compared to non-treated groups (i.e. only designed experiments that included a control were included and observational studies were omitted); 2) experiments were conducted in a field setting (i.e. greenhouse studies were not included), and 3) studies measured a change in aboveground abundance or survival of field bindweed or Canada thistle (i.e. percent cover, density, biomass, and percent control) in response to a treatment. In addition, since our study was meant to inform perennial weed management in organic systems, synthetic herbicides could not have been applied to experimental units of interest at any point during a study. It is important to note that we did not require studies to be conducted in certified organic systems in order to be included. For example, synthetic herbicides could have been applied to some of the plots in a given study, but we required at least one comparison between a non-herbicide management tactic and a non-treated control for a paper to be included in our analyses. Finally, studies were excluded if synthetic herbicides were used as site preparation in all experimental units.

Studies conducted in all agronomic systems and geographic areas were included. Records were subjected to a number of filters to identify studies appropriate for our questions of interest based on the criteria described above (Fig. 1a and b). Titles and abstracts of all studies were screened, and those that did not meet our criteria were omitted. The full text of the remaining articles was then assessed for inclusion in the study. All literature screening and review was conducted by the same author (Noelle Orloff).

2.2. Data extraction

There were several potential sources of non-independence in our data set. Following Gurevitch and Hedges (2001) we mitigated their potential impact in this study by developing pre-determined criteria to define which data points to extract from each article. For example, for studies that reported results over several time points (i.e. repeated-measures studies), we extracted data from the last reported time. Similarly, for studies that reported results for multiple levels of a factor, we extracted data from the highest factor level (i.e. highest concentration of bioherbicide, closest row spacing, greatest number of tillage events, etc). When the highest level of the factor was not obvious, we pooled levels of the factor (i.e. variety trials, ecotypes of weeds). If studies were replicated across more than one location or multiple trials were conducted at the same location, we considered the responses independent in each location and trial.

Retaining more than one response variable for a given experimental unit also introduces problematic pseudo-replication to meta-analyses (Gurevitch and Hedges, 2001). In 21% of studies selected for analysis, there were two or more response variables reported for the same experimental unit. To reduce potential bias, if two abundance response variables were reported for the same experimental unit in the same study, we selected the response we considered most useful for describing perennial weed abundance in agroecosystems. To achieve this goal, and based on the life history and growth habit of field bindweed and Canada thistle, we extracted response variables in a pre-determined order of importance (biomass > percent canopy cover > density >

frequency > survival > percent control). In some cases, the control treatment reported by the original author was not the same as what we would define as a control for the purposes of our meta-analyses, so we switched the treated and control groups (Gurevitch and Hedges, 2001). Non-treated control treatments in our analysis were assigned as the treatment with the least management inputs. For example, if a study investigated the effect of reduced tillage on a weed community, we used the reduced tillage treatment as our control group and the conventional tillage treatment as our treated group. The mean, sample size, and standard deviation or standard error (when available) values were extracted for each response in each paper for a treated group and a non-treated group of field bindweed or Canada thistle. Finally, we extracted background information about each study including study location, publication year, and duration of study.

2.3. Data analysis

In meta-analysis, effect size is calculated for each experiment to create an index of treatment effects (Gurevitch and Hedges, 2001). When possible, meta-analyses use equations that require standard deviation to weight effect sizes, but very few of the studies we identified reported measures of variability (16% of field bindweed and 26% of Canada thistle studies). To include as many studies as possible, following Lajeunesse (2014), we used the response ratio (ln*R*) as our effect size, an estimate that does not require variability and was calculated as:

$$\ln R = \ln(X_T/X_C),$$

where X_T = treatment mean and X_C = control mean.

This metric cannot be calculated in situations where the treatment or control mean equals zero, which was the case for 6% of studies across both species considered in our analyses. These studies were not included in further analysis. Following Lajeunesse (2014), we weighted each response ratio using sample sizes rather than standard deviation:

$$\sigma^2(\ln R) = n_T n_C/(n_T + n_C),$$

where n_T = treated group sample size and n_C = control group sample size. We used bootstrapping methods with 1000 iterations to calculate a mean effect size and 95% confidence interval (CI) for each treatment category (Adams et al., 1997). We considered a treatment effect to be different than zero if the CI did not overlap zero, and treatments to be different than one another if their CIs did not overlap (Gurevitch et al., 1992).

For both field bindweed and Canada thistle, we conducted separate meta-analyses of management in annual systems (i.e. annual crops and fallow) and perennial systems (i.e. pasture, rangeland, vineyard). Limited replication within treatment categories precluded further splits beyond annual/perennial systems. All analyses were conducted using R statistical software, including the package ggplot2 (R Development Core Team, 2016; Wickham, 2009), following methods outlined by Lajeunesse (2014). We delineated fifteen treatment categories used to manage field bindweed and Canada thistle and performed our analyses to determine if there were differences in efficacy among categories (Table 1). A complete bibliography of the papers used in our analyses is reported in Appendices A and B. The variables extracted from each paper used in the analyses including authors, date of publication, duration of study, agricultural system, and management techniques used in each paper are presented in Appendix C through F.

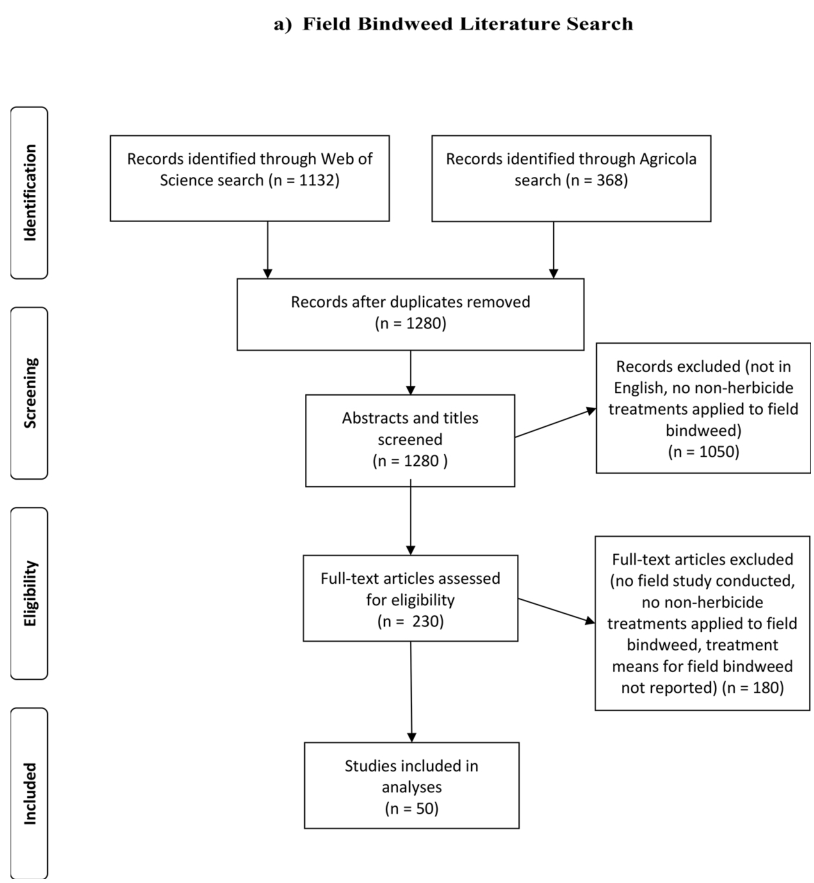

Fig. 1. Flow chart depicting filters applied during literature screening portion of the systematic review of the a) field bindweed and b) Canada thistle management databases. In each box, n is the number of records described in that step.

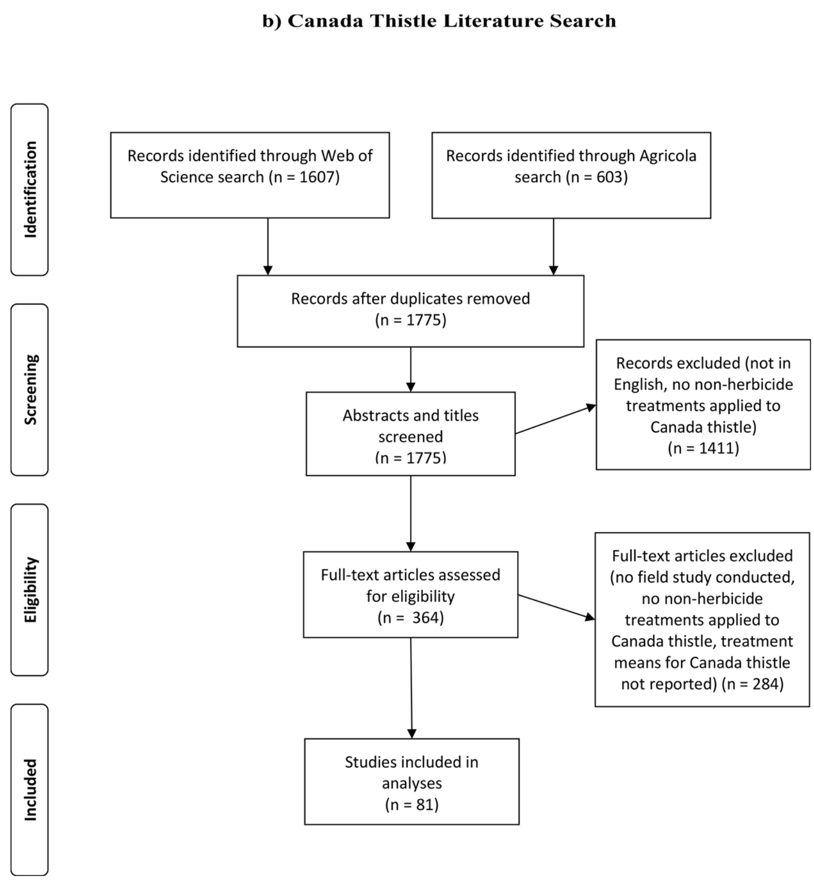

Fig. 1. (*continued*)

3. Results

3.1. Literature review

Initial literature searches resulted in 1280 and 1775 unique records for field bindweed and Canada thistle, respectively. As a result of our screening process, we collected a total of 50 field bindweed papers that met the criteria stated above and were subsequently used for our meta-analyses (Fig. 1a). Of these, 30 were conducted in annual systems, 14 were conducted in perennial systems, and six were conducted in both annual and perennial systems. We were unable to use data from two field bindweed studies because ln*R* could not be calculated due to the treatment or control mean equaling zero (). We collected 81 Canada thistle papers that met our criteria for inclusion in the analyses (Fig. 1b). Of these, 35 studies were conducted in annual systems, 42 were conducted in perennial systems, and four were conducted in both annual and perennial systems. We were unable to use data from six of the 81 papers because ln*R* could not be calculated.

There were several interesting patterns in the dataset. First, the timing and number of publications can be used as an indicator of how interest in non-chemical weed control in the absence of synthetic herbicides has changed between 1935 and 2014. There were ten publications on field bindweed control in the pre-herbicide era (1935–1955) and only two in the two subsequent decades when use of synthetic herbicides became widespread (Fig. 2a). For both species there has been a substantial increase in research about non-herbicide control methods in the last twenty years, with two-thirds and three quarters of studies published since 1995 for field bindweed and Canada thistle,

Table 1
Treatment categories used to conduct a *meta*-analysis of organic Canada thistle and field bindweed management tactics.

Categories	*Description*
Biocontrol	Biological control achieved with natural enemies (insects or pathogens)
Bioherbicide	Plant extract used as bioherbicide
Burn	Prescribed burn used in perennial systems such as natural areas
Competition	Treatment designed to increase crop competitive ability, i.e. ridge sowing, manipulating row spacing, intercropping, revegetation, and cultivar trials
Crop Diversification	The addition of different crops or plants into a cropping system. Examples include adding cover crops or increasing crop rotation within a cropping system
Flaming	Flame weeding using propane torch in annual cropping systems
Flooding	Inundating with water
Grazing	Using animals to graze field bindweed and Canada thistle
Integrated	Any combination of two or more control methods.
Mechanical	Any mechanical control method including hand or mechanical hoeing, hand weeding, and cultivation
Mowing	Mowing the plot
Mulch	Use of either plastic or organic mulches
Shading	Reduction in light availability using shade cloth
Soil Amendments	Soil amendments meant to increase nutrient availability including animal manure or fertilizer applied
Solarization	Heating the soil by covering them with dark or translucent plastics

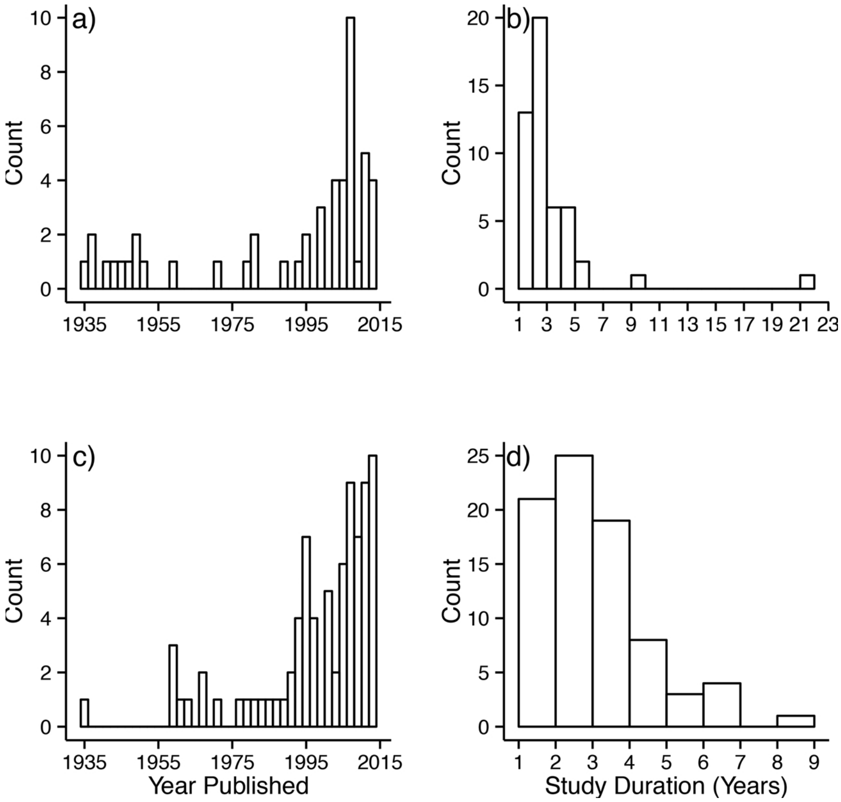

Fig. 2. Histograms depicting year published (a, c) and study duration (b, d) for non-herbicide field bindweed (a, b) and Canada thistle (c, d) management studies.

respectively (Fig. 2a and c). Second, most studies evaluated relatively short-term effects of management on these long-lived weeds. Of the studies used in our analyses, 53% were conducted for a period of one to two years, while just 9% were conducted for five or more years (Fig. 2b and d). Third, management of these weeds has received attention around the globe. Field bindweed studies were conducted in 16 countries, while Canada thistle studies were conducted in 23 countries. Twenty-six of 50 field bindweed studies were conducted in North America, with three studies conducted each in Hungary, Pakistan, Switzerland, and Turkey. Twenty-nine of 81 Canada thistle studies were conducted in North America, and 13 studies were conducted in New Zealand and five in Germany.

3.2. Meta-analysis – field bindweed

In annual systems two management techniques emerged as causing the largest decrease in field bindweed (Fig. 3a). These include integrated management, defined as the combination of two or more control methods over the course of one study, as well as propane flaming. In the integrated management category, which was derived from four studies, all but one of the 18 data points represent treatments that integrated tillage and sowing competitive vegetation. Three of the four studies in this category were published prior to 1950. Flaming was investigated by researchers in one study with three data points.

Several single practices were less effective than integrated management but still reduced field bindweed abundance in annual systems (Fig. 3a). These practices included biocontrol, crop diversification, mechanical control, mulch, solarization, and competition. All of these treatments had similar effectiveness to one another. The use of a bioherbicide did not impact field bindweed, and soil amendments increased field bindweed (Fig. 3a). It is important to note that soil amendments were represented by only one observation in our analysis, so we could not calculate a confidence interval around the response ratio.

In perennial systems, most of the field bindweed treatment categories had similar effectiveness to one another, and most decreased field bindweed (Fig. 3b). The exceptions were mowing, grazing, and mulch, which had no detectable impact on field bindweed, but it is important to note that these methods were only represented by two, two, and three data points, respectively. Shading reduced field bindweed abundance slightly more than many of the other categories, with the exception of integrated management and competition.

3.3. Meta-analysis – Canada thistle

Solarization and shading caused the largest decrease in Canada thistle in annual cropping systems (Fig. 4a). However, these two methods were not well represented in the literature. For example, we used one data point to determine the response ratio for shading and were not able to calculate a confidence interval to assess its relative efficacy compared to the other methods in this analysis. Integrated management was similar in effectiveness to solarization, as well as the next most effective group of methods including mechanical control, biocontrol, and crop diversification. Mowing, competition, and soil amendments did not impact Canada thistle abundance. In perennial systems integrated management, grazing, competition, biocontrol, mowing, and mulch all decreased Canada thistle similarly (Fig. 4b). Soil amendments, irrigation, and burning had no detectable effect on Canada thistle.

4. Discussion

Organic management of perennial weeds in agricultural systems is an old challenge, and the date range of papers used in our analysis (1935-present) and number of studies conducted about managing Canada thistle and field bindweed reflect this fact. Overall, our results suggest that there are general recommendations we can make to help reduce perennial weed abundance in organic agricultural systems. This study also highlights opportunities for future research. Furthermore, our findings emphasize the importance of including measures of

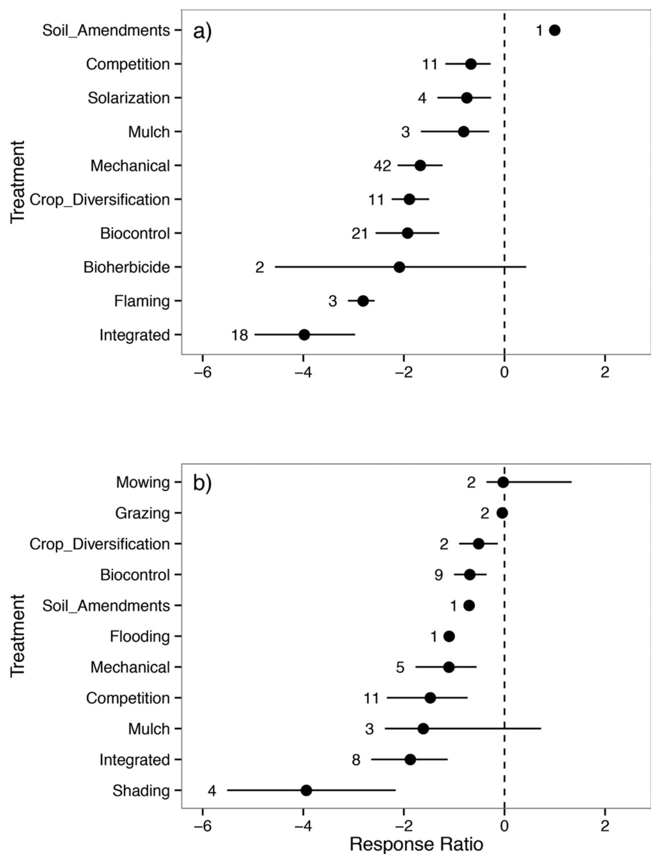

Fig. 3. Mean effect sizes, or response ratios and 95% confidence intervals (lines and brackets) for organic field bindweed control in a) annual and b) perennial cropping systems. More negative means correspond with a greater decrease in field bindweed abundance. Control methods decrease field bindweed abundance if the confidence intervals do not cross zero (dotted line). Control methods are different from one another if confidence intervals do not overlap. For each method, n (the number located to the left of the confidence interval) is the number of observations that was used to calculate the mean.

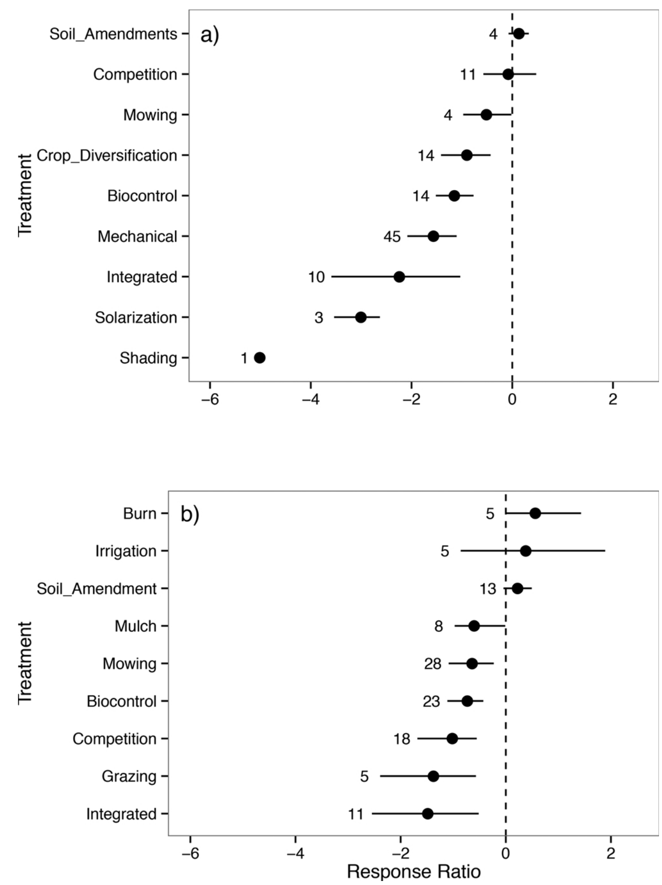

Fig. 4. Mean effect sizes, or response ratios and 95% confidence intervals (lines and brackets) for organic Canada thistle control in a) annual and b) perennial cropping systems. More negative means correspond with a greater decrease in Canada thistle abundance. Control methods decrease bindweed abundance if the confidence intervals do not cross zero (dotted line). Control methods are different from one another if confidence intervals do not overlap. For each method, n (the number located to the left of the confidence interval) is the number of observations that was used to calculate the mean.

variability in published research results. Surprisingly, few of the studies we used in our analyses included this vital piece of experimental information, and we were not able to conduct a traditional meta-analysis as a result of this systematic omission.

A striking finding of these analyses was that average study length was relatively short, with fewer than 10% of the reviewed studies considered in our meta-analyses being conducted for five or more years. As perennial species, field bindweed and Canada thistle have long life spans and extensive root systems that can persist for many years (Hakansson, 2003a). Perennial weed populations recover from many management interventions used in organic systems due to carbohydrates stored in deep roots (Bakke et al., 1939; Barr, 1940) and would require additional management inputs to prevent competition with future crops. However, management inputs at high frequencies may not be economically or environmentally sustainable and additional long-term studies are needed to fully evaluate the extent to which any proposed practice could be implemented to successfully manage these perennial weed populations in organic agricultural settings. Most of the treatments we investigated resulted in a decrease in perennial weed abundance in experimental settings, yet these two species remain a substantial problem across systems in practical settings (Tautges et al., 2016). These results suggest that even though we can reduce the abundance of these two species temporarily using current management techniques, we do not seem to be successfully managing them over a longer time period in annual or perennial systems without the use of synthetic herbicides.

Frequent and intensive tillage has traditionally been the mainstay of perennial weed management in the absence of herbicides (Tautges et al., 2016), and mechanical control was the most researched method of the papers we reviewed, particularly in annual systems for both field bindweed and Canada thistle. For example, for field bindweed in annual systems we found 42 data points representing mechanical control, and for Canada thistle in annual systems we found 45 data points, representing about 40% of the data we collected. Yet, according to our results mechanical control did not outperform the majority of other management techniques for either species in annual systems. Although frequent cultivation, plowing, or even hoeing can effectively control field bindweed and Canada thistle (Hodgson, 1958; Timmons, 1941; Tingey, 1934), the overall efficacy of the different mechanical control practices in our analyses was variable, ranging from nearly 100% control to slight increases in abundance of target weeds. One reason for this variability may be the variety of different implements and methods (type, depth, timing, and frequency) used in mechanical weed management. Furthermore, whether tillage systems were designed to effectively deplete the root reserves of these weeds is likely a key factor in its efficacy (Mohler, 2001b), and these considerations likely also explain much of the variability in efficacy that we observed. For example, Timmons (1941) found that in clonal populations, field bindweed root energy reserves declined for about two weeks after bindweed emergence while the root system supported emerging shoots. After this point, root reserves increased as carbohydrates were transported from above to belowground tissues. Timmons (1941) also found that tillage frequency that matched this biological pattern reduced field bindweed densities most rapidly.

Mechanical control can be a valuable tool in perennial weed management, but concerns remain about its impact on erosion and soil health. To our knowledge, mechanical control practices that damage weed root systems but avoid inversion tillage have not been investigated with the specific purpose of managing these perennial weeds, though researchers in organic systems have noted increases in perennial weeds under reduced tillage systems (i.e. Armengot et al., 2015; Sans et al., 2011). Using undercutters, minimum disturbance cultivators, subsoilers, and other non-inversion tillage implements in a way that targets perennial weed biology may deliver similar efficacy to more traditional cultivation methods while retaining crop residue on the soil surface, avoiding potential soil losses. Our results provide support for further investigation and adoption of reduced tillage organic cropping systems, a critical research challenge (Armengot et al., 2015).

Another important management strategy used in organic annual systems to not only control weeds, but also to limit disease spread and promote soil health is the concept of crop diversification (Liebman and Staver, 2001). In our study, we defined this category as the addition of different crops to a system either over time or within a field. This category included methods such as smother crops, cover crops, intercropping, and increasing crop rotation diversity, and was comprised of four field bindweed studies and seven Canada thistle studies. As a whole, this category did not outperform the majority of other methods, but it is worth examining the contribution of each specific method within the category. For example, in the Canada thistle analysis changes in abundance ranged from reductions of 96% to increases of 50%. In the study with the largest reduction in Canada thistle for this category, McKay et al. (1959) established a stand of alfalfa and grass for two years, followed by potatoes. Compared to the control plots which were continuously cropped spring wheat plots for those three years, there was a 96% reduction in Canada thistle. All other studies in this category investigated the use of cover crops, with the largest decreases in Canada thistle resulting from cover crop mixes (i.e. Wedryk and Cardina, 2012; Bicksler and Masiunas, 2009; Wedryk et al., 2012; Thomsen et al., 2011). The large decreases in perennial weed abundance observed in some studies in this category suggest diversifying cropping systems or seed mixes with the aim of managing perennial weeds is a promising management option.

Biological control, or the use of organisms such as insects or pathogens to manage weeds, was studied across systems and overall caused a moderate to low decrease in weed abundance compared to other management categories. However, the relatively large dataset available for this method compared to others in our analysis suggests an interest in this control method. For field bindweed, there were nine papers representing 30 data points. For Canada thistle, there were 18 papers representing 37 data points. In general, across all systems, biological control with pathogens was more effective and more widely researched compared with biological control using insects. The organisms that were most effective in reducing field bindweed abundance in annual systems were pathogens including *Phoma* species (i.e. Vogelsgang et al., 1998; Heiny, 1994). In perennial systems pathogen *Stagonospora convolvuli* was most effective in reducing field bindweed (i.e. Boss et al., 2007). For Canada thistle pathogens were again investigated more often than insects, and the most effective pathogens in annual systems were *Puccinia punctiformis* and *Sclerotinia sclerotiorum* (i.e. Tipping, 1993; Brosten and Sands, 1986), with beetle *Cassida rubiginosa* showing promise in controlled settings (Asadi et al., 2013). In perennial systems applications of pathogens *P. punctiformis* and *S. sclerotiorum* were most effective in reducing Canada thistle abundance (i.e. Hurrell et al., 2001; Watson and Keogh, 1980). Despite the efficacy of certain biological control agents in reducing weed abundance, it is difficult to make recommendations about use of these organisms as their commercial availability and regulatory considerations vary in different regions of the world. Further, the success of these biological control agents in decreasing weed abundance depends on environmental conditions that vary year to year and site to site.

Shading was investigated in two studies across systems, and in both cases it caused a substantial decrease in field bindweed and Canada thistle. This method has not been well-researched and was represented by one field bindweed study and one Canada thistle study. Bakke and Gaessler (1945) shaded small plots of field bindweed in a fallow setting with several types of cloth that had different light transmission values; shading decreased field bindweed abundance by 76% to 99% for the one year that the study was conducted. In the study focusing on Canada thistle control, Hettwer et al. (2002) used plastic shade nets to decrease light transmission by 15% in May and 5% in June and July. While the goal of this study was to mimic the effect of wheat shading on Canada thistle rather than to study the effect of shading itself, it reduced weed biomass by almost 100%. These results not only highlight the importance of crop competition as a viable approach to perennial weed management (Mohler, 2001a) and elucidate one of the mechanisms behind it, but they also suggest future research that could evaluate the potential of shading techniques for small areas.

Soil solarization showed promising results for Canada thistle control and decreased field bindweed to a lesser degree. In the only study where solarization was assessed as a method to manage Canada thistle, solarization with clear plastic caused a 98% reduction in abundance (Candido et al., 2011). Solarization of field bindweed was only represented by two studies (Elmore et al., 1993; Zasada et al., 2003), both conducted in relatively small-scale systems. Elmore et al. (1993) applied a clear tarp to fallow areas for nine weeks leading to 81% reductions in field bindweed, while Zasada et al. (2003) applied a clear tarp for six weeks leading to 16% to 57% reductions in field bindweed. While this method seems to be effective, these were short-term experiments that reported field bindweed response after one year of treatment application. It would be beneficial to investigate longer-term effects of this management technique, and future studies could evaluate the integration of solarization followed by competitive crops or cover cropping in long-term settings. However, while this approach could be adopted on a small spatial scale or at early stages of infestations, it is unlikely that it could be implemented on a large scale.

One of the clearest results and suggestions for future research topics to emerge from this project is that integrating intensive tillage either post-harvest or during fallow followed by sowing of competitive crops appears to be an effective field bindweed management technique in annual cropping systems. For example, in multi-year studies Stahler (1948) and Wilson et al. (1942) both explored intensive cultivation followed by seeding a variety of competitive crops including corn (*Zea mays* L.), hemp (*Cannabis sativa* L.), sorghum [*Sorghum bicolor* (L.) Moench], soybeans [*Glycine max* (L.) Merr.], and sudangrass [*Sorghum* X *drummondii* (Nees ex Steud.) Millsp. & Chase], which led to field bindweed reductions of 90% to 99%. Timmons (1949) reported that cultivation combined sorghum sown with decreased row spacing reduced field bindweed by 67% over four years. In a more recent study, Bilalis et al. (2003) investigated minimum tillage combined with mulch in a fava bean (*Vicia faba* L.) crop for one year, leading to a 79% decrease in field bindweed. Determining appropriate frequency, type, and timing of tillage to maintain soil health and identifying regionally adapted and profitable competitive crops to use with such an integrated approach would be a fruitful area for field trials and on-farm research. Multi-disciplinary research efforts that combine ecological and economic impacts of these types of actions would help determine what types of weed management systems would be profitable and ecologically sustainable in the long term.

For field bindweed in annual systems, propane flaming also emerged as a potentially effective treatment. In the one year flaming study conducted by Ulloa et al. (2010), researchers observed 92% to 96% decreases in field bindweed abundance as a result of broadcast propane flaming. While a combination of banded flaming followed by aggressive cultivation has the potential to effectively control annual weed species in organic systems (Stepanovic et al., 2016), the extent to which this approach can be used to reduce the spread and impact of perennial weeds over a longer time period is, to our knowledge, largely unknown. As with other perennial weed control methods, timing flaming treatments to have the greatest negative impact on weeds and integrating with other control methods may be the most promising approach.

5. Conclusion

5.1. Management recommendations

Broad management recommendations can be delineated based on our results and systematic review of the literature. First, integrating tillage post-harvest or during fallow followed by sowing of competitive crops or cover crops can effectively decrease field bindweed abundance and survival in annual cropping systems. Second, intensive tillage practices can effectively control these species. However, although mechanical control was the most researched single method for both species in annual systems, it did not outperform the majority of management techniques as a whole. Though this result is partly due to the variation in mechanical control practices investigated in the literature, it suggests that alternative methods of weed control may be as effective as tillage while maintaining soil health. One such alternative option may be incorporating a year of cover crops or another competitive crop into a rotation. Third, short-term management techniques such as propane flaming and soil solarization may be effective means of managing these species, but more long-term information about these methods is needed.

5.2. Future research

Several directions for future research were identified from the results of this study. First, longer-term experiments would be beneficial to assess the potential of integrated management practices to reduce abundance and impact of perennial weed species in organic systems. Most of the management techniques evaluated in this project led to a decrease in perennial weed abundance and survival in the relatively short time periods investigated, but investigations over a longer time period may help identify the most useful methods in the field. There is a need for longer-term research focused on sustainable perennial weed management systems in addition to short-term interventions. Second, integrating mechanical control methods with sowing of competitive vegetation can effectively decrease field bindweed abundance and survival in annual cropping systems. Tillage as a stand-alone method can also effectively decrease field bindweed and Canada thistle populations. However, determining appropriate tillage methods to maintain soil health and identifying regionally adapted and profitable competitive crops to use with such an integrated approach is required in order to design sustainable management tactics. It would also be worthwhile to develop and assess the viability of reduced-tillage systems and non-inversion tillage methods that can help manage these species. Solarization and shading may warrant further research given the decrease in Canada thistle in response to these control methods, albeit from a limited number of investigations. For all of these future research opportunities, it would be beneficial to undertake multi-disciplinary assessments to make sure recommendations are economically and ecologically viable and sustainable. Finally, it is critically important that future weed management studies report estimates of variability to allow inter-research comparisons.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.agee.2017.11.024.

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