MN NWAC Risk Assessment Worksheet (04-2011)	Common Name	*Latin Name*
	Plumeless Thistle	*Carduus acanthoides* L.
Original Reviewer: Ken Graeve	Affiliation/Organization: MnDOT	Original Review Date: 08-07-2013
Current Reviewer: Roger Becker	Affiliation/Organization: UMN	Current Review Date: 07-18-2019

2019 Summary:
This is an update for plumeless thistle only, building on the combined plumeless and musk thistle risk assessment on file by Ken Graeve in 2013. Plumeless thistle is a non-native biennial plant first recorded in Minnesota in 1949 (Bell Museum) that has long been a problem in disturbed sites and heavily grazed or droughty pastures on well drained soils. Plumeless thistle is now is the most common biennial thistle throughout the state (Becker personal observations). Most of the literature on *Carduus* thistles is on musk thistle (*C. nutans*) as musk thistle historically has been a significant problem more broadly across North America. Large infestations of musk thistle have since been successfully suppressed with biological control, mostly due to the introduction of *Rhinocyllus conicus*.

Plumeless thistle is not seen as a serious ecological threat in native systems in Minnesota, with most ecological restoration practitioners seeing it as a symptom of disturbance that diminishes as a plant community is restored. Plumeless thistle is problematic in sparsely vegetated and overgrazed pastures, often the result disturbance or openness of drought-prone pastures rather than invasion and displacement of desirable forages. Plumeless thistle is too widespread for eradication or containment. The *Rhinocyllus conicus* weevil introduced for biological control of musk thistle minimally impacts plumeless thistle. It can be easily managed with herbicides in grass systems, or via improved pasture management where feasible. Although plumeless thistle is a significant concern for some livestock producers and causes economic impact, it is difficult to quantify the significance of that impact.

This 2019 risk assessment recommends maintaining the Prohibited Noxious Weed on the Control List status for plumeless thistle for the following reasons:

- The widespread distribution of plumeless thistle prevents any meaningful chance of its eradication or containment
- Though widespread agricultural impact is not well documented, localized economic impact can be significant as described in box 8 C
- Plumeless thistle can be a symptom of overgrazing or other disturbance, but that is the reality of pasture systems on low productivity soils in low-input droughty pastures. If local seed production is not contained and minimized, seed-bank driven invasion can overwhelm some pasture systems requiring control expenditures that otherwise may be avoided if localized seed production is minimized

- Where feasible, improved pasture management is most likely the best strategy for reducing the impacts of plumeless thistle, yet preventions of localized seedbank expansion can be supported via the noxious weed law

Current Regulation: Minnesota Prohibited Noxious Weed on the Control List.

2013 summary by K. Graeve:
Musk and plumeless thistles are two non-native biennial weeds that have long been a problem in disturbed sites and heavily grazed pastures. Both are widespread in Minnesota and North America. Historically, musk thistle has been more common in the southern half of Minnesota and plumeless thistle more prevalent in the northern half of the state (Cortilet). Currently plumeless thistle may be spreading into more of the state and possibly displacing musk thistle in some areas. These species are much too widespread for any hope of eradication or containment. Both are impacted by a non-native weevil called *Rhinocyllus conicus*, but this insect does not sufficiently limit their spread, and it also feeds on several native species (Gassmann and Kok).

These thistles are not seen as a serious ecological threat in Minnesota, with most ecological restoration practitioners seeing them as a symptom of disturbance that diminishes as a plant community is restored (Graeve). Musk and plumeless thistles are problematic in overgrazed pastures, but are a result of that disturbance rather than a primary problem, and are easily managed with herbicides or improved pasture management (Hartzler, Becker). Although these thistles are probably of concern for some livestock producers and have some economic impact, it is difficult to quantify the significance of that impact. Of the two, Plumeless thistle is believed to be a more serious threat because it appears to be better able to invade less degraded pastures (Chandler).

This risk assessment recommends removing musk and plumeless thistle from the noxious weed list for the following reasons:

- It is difficult to show that the agricultural impact of these thistles is significant as defined in box 8
- Musk and plumeless thistle become problems as a result of overgrazing or other disturbance and are not the ultimate cause of decreased forage yields or increased production costs
- Musk and plumeless thistle are easily controlled through improved pasture management or herbicide treatment
- The widespread distribution of both species prevents any meaningful chance of their eradication or containment
- Improved pasture management is most likely the best strategy for reducing the impacts of these thistles rather than regulation under the noxious weed law

Box	Question	Answer	Outcome
1	Is the plant species or genotype non-native?	Yes. There are six *Carduus* species in the U.S., all six are introduced, and all are "plumeless" [no side branching (feathers) on pappus spines]. Only *Carduus acanthoides* (plumeless thistle) and *C. nutans* (musk thistle) are present in MN (Figure 1. PLANTS 2019). Plumeless thistle is native to Europe ranging from France, Italy, and western Turkey; through Russia and Kazakhstan; to China (Wikipedia 2019). In its native range the plant is found in open grasslands and disturbed areas.	Go to Box 3
2	Does the plant species pose significant human or livestock concerns or has the potential to significantly harm agricultural production?		
	A. Does the plant have toxic qualities that pose a significant risk to livestock, wildlife, or people?		
	B. Does the plant cause significant financial losses associated with decreased yields, reduced quality, or increased production costs?		
3	Is the plant species, or a related species, documented as being a problem elsewhere?	Yes. Widespread problem in north America. Present in six Canadian provinces and 46 states in the U.S., with a noxious weed designation in 14 states (PLANTS 2019). First recorded in North America in the U.S. in New Jersey in 1879 (Desrochers et al. 1988) and in Ontario Canada in 1907 (Rousseau and Raymond 1945 as cited by Moore and Frankton 1974).	Go to Box 6
4	Is the plant species' life history & Growth requirements understood?		
5	Gather and evaluate further information:		

Box	Question	Answer	Outcome
6	Does the plant species have the capacity to establish and survive in Minnesota?		
	A. Is the plant, or a close relative, currently established in Minnesota?	Yes. Widespread in Minnesota (Figure 2. EDDMapS 2019). Historically most problematic on the beach ridge pasture systems in NW Minnesota (personal observation). The first record of plumeless thistle in the Bell Museum (accessed June 25 2019) is from Fargo ND in 1947, soon followed by two Minnesota records in 1949, in Becker and Rock counties and now records exist throughout Minnesota (Figure 3). EDDMapS currently lists 2777 points across 56 counties in Minnesota (Figure 4), far exceeding the next highest reporting states, 848 in CO, and 733 in PA (EDDMapS 2019). Plumeless thistle is the most common biennial thistle in Minnesota, as seen in the distribution of introduced and native thistles recorded as part of the Plant Pest Survey (Figure 5, MDA 2003).	Yes, go to Box 7
	B. Has the plant become established in areas having a climate and growing conditions similar to those found in Minnesota?	***Yes***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
7	Does the plant species have the potential to reproduce and spread in Minnesota?		
	A. Does the plant reproduce by asexual/vegetative means?	No. Biennial reproducing by seed (Desrochers et al. 1988).	Go to Box 7 C
	B. Are the asexual propagules effectively dispersed to new areas?		
	C. Does the plant produce large amounts of viable, cold-hardy seeds?	Yes. Plumeless thistle averaged around 8,400 seeds per plant for the plumeless thistle in North Dakota (Lym 2013). Desrochers et al (1988) referenced unpublished data by Warwich and Thompson of 56 to 83 seeds produced per seedhead, and Feldman and Lewis (1990) documented 10 to 85 capitula (flowering seedheads) per plant. From this an estimated 560 to 7055 viable seed could be produced per plant.	Yes, go to Box 7 F

Box	Question	Answer	Outcome
	D. If this species produces low numbers of viable seeds, does it have a high level of seed/seedling vigor or do the seeds remain viable for an extended period?		
	E. Is this species self-fertile?	***Limited self-pollination in C. acanthoides which is primarily an outcrossing species. C. nutans and C. acanthoides can hybridize. Hybrids tend to have low seed production. (Desrochers et al. 1988).***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
	F. Are sexual propagules – viable seeds – effectively dispersed to new areas?	Yes. Dispersed by wind with most traveling 2 m from the mother plant, though several traveled 8 m and beyond a trapping array (Feldman and Lewis 1990). Heavier musk thistle seed dispersed mainly within 50 m of the parent plant with <1% carried further than 100 m (Smith and Kok 1984). Significant secondary dispersal by insects and small mammals has been shown locally for plumeless thistle (Jongejans et al. 2015). Movement in hay and equipment is likely a primary means of long-distance dispersal (Becker, personal observation).	Go to Box 7 I
	G. Can the species hybridize with native species (or other introduced species) and produce viable seed and fertile offspring in the absence of human intervention?	***No with native Cirsium. See 7. E. above. There are no native Carduus in the U.S.***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
	H. If the species is a woody (trees, shrubs, and woody vines) is the juvenile period less than or equal to 5 years for tree species or 3 years for shrubs and vines?		

Box	Question	Answer	Outcome
	I. Do natural controls exist, species native to Minnesota, which are documented to effectively prevent the spread of the plant in question?	No. A non-native weevil, *Rhinocyllus conicus,* that feeds on flower heads of *Carduus* species is widespread and has reduced the density of *C. nutans* infestations (Becker, personal observation, Gassman and Kok 2002). *Rhinocyllus conicus* is reported to have minimal impact on plumeless thistle (Kok 2001). A 2003 survey showed 11% (5 of 44) plants sampled were attacked by *Rhinocyllus conicus* as part of the Plant Pest Survey (MDA 2003). *Trichosirocalus horridus* is reported to be more impactful on plumeless thistle (Kok 2001) but its status in MN is not known.	Go to Box 8
8	Does the plant species pose significant human or livestock concerns or has the potential to significantly harm agricultural production, native ecosystems, or managed landscapes?		
	A. Does the plant have toxic qualities, or other detrimental qualities, that pose a significant risk to livestock, wildlife, or people?	No. No toxic qualities. Spines inhibits grazing, but the effects of this are covered in box 8 B.	Go to 8 B
	B. Does, or could, the plant cause significant financial losses associated with decreased yields, reduced crop quality, or increased production costs?	Yes. Economic benefit of control or cost of non-control are not well documented. Generally, plumeless thistle is reported to invade overgrazed grasslands, leading to characterizing the presence of plumeless thistle as a management problem, but Renz and Schmidt (2012) found that plumeless thistle seedling population density did not decrease with increased forage canopy height, possibly due to its reported ability to germinate in low light intensities (Feldman et al. 1994). It is true plumeless thistle is problematic in overgrazed pastures, and it can be easily managed with herbicides in grass monocultures or with improved pasture management (Hartzler ISU, Becker UMN Personal communication). However, many grazing systems are on land not suitable for cropping, and a subset of these are inaccessible or unsuitable for improved management techniques such as interseeding legumes or improved pH and fertility e.g. due to	Go to Box 9

Box	Question	Answer	Outcome
		topography, numerous stones, low productivity unirrigated beech sands, etc. These low input systems can be profitable for grazing, but are susceptible to invasion by plumeless thistle, esp. on droughty soils such as the beech ridge pastures in northwestern Minnesota bordering Lake Agassiz (Becker personal observations) where open niches are common for invasion. Additionally, use of herbicide to control plumeless thistle will kill or significantly suppress forage legumes in grass : legume systems. Estimates suggest annual losses to agricultural production in 2002 in Nebraska were at $162,000 in 2002 dollars, infesting 65,000 acres of grazing lands (Hilgenfeld and Martin 2002). Graeve in the 2013 review cited cattle sales in Nebraska for the same year totaled $5.1billion (Petersan & Frederick 2002), in light of which the costs quoted by Hilgenfeld and Martin (2002) seemed rather insignificant. Recent figures by McClure ad Lubben (2018) show $11.2 billion total receipts for beef and dairy combined sales in Nebraska in 2016, but no updated loss estimates for plumeless thistle could be found. Comparing losses to total receipts as reported by Grave in the 2013 review dilutes the potential for economic losses due to plumeless infestations across all grazing lands. Since plumeless thistle most impacts vegetatively open sand pastures (personal observations), economic losses are likely disproportionally occurring on poor producing pasturelands rather than in all grazing lands. Where plumeless thistle is problematic, the economic loss can be significant to individual producers. **2012 risk assessment response to Question 8B:** No. Musk and Plumeless thistles are problematic in overgrazed pastures, but are a result of that disturbance rather than a primary problem, and are easily managed with herbicides or improved pasture management (Hartzler, Becker 2013). Thistles compete poorly with healthy established grasses and require some disturbance such as fire, overgrazing, or trampling to encourage colonization (CDFA 2013).	

Box	Question	Answer	Outcome
		Although these thistles are probably of concern for some livestock producers and have some economic impact, it is difficult to quantify the significance of that impact. Ten-plus year-old estimates in 2002 suggest annual losses to agricultural production in Nebraska were at $162,000 (Hilgenfeld and Martin 2002). However, cattle sales in Nebraska for the same year totaled $5.1billion (Petersan and Frederick 2002), making the costs quoted by Hilgenfeld and Martin (2002) seem rather insignificant. Gassmann and Kok (2002) state that a musk thistle infestation of one plant per 1.49m2 can reduce pasture yields by 23%. However, although their figure is widely quoted, it seems to be theoretical and based on a simple calculation of the size of a thistle plant, and there is no evidence to support the logical conclusion that there would be 1/3 more beef production in the Midwest if it weren't for musk and plumeless thistles. State of Victoria estimates forage yield reductions of 13% are possible. The economic impacts may be less than they used to be because more producers are using rotational grazing systems that work to prevent large thistle infestations and also because the seedhead weevil seems to have some detrimental impact on the competitive ability of *C. nutans* (Becker 2013). Of the two, Plumeless thistle is believed to be a more serious threat because it appears to be better able to invade less degraded pastures (Chandler 2013).	

Box	Question	Answer	Outcome
	C. Can the plant aggressively displace native species through competition (including allelopathic effects)?	***No. Plumeless thistle is common in newly renovated or established prairies responding to disturbance niches made available but do not persist beyond the 3rd or 4th year following prairie seeding. Plumeless thistle occurs sporadically in established prairie and are not a concern (Becker personal observations). These thistles are not a big threat to established native plant communities in Minnesota, according to an informal survey of over two dozen experienced ecological restoration practitioners around the state, in which the overriding sentiment was that these thistles form dense stands only as a result of disturbance and they fade away as a plant community recovers (Graeve 2013 assessment).***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
	D. Can the plant hybridize with native species resulting in a modified gene pool and potentially negative impacts on native populations?	***No. No mention found of hybridization with native species, but C. nutans and C. acanthoides will hybridize with each other (see Box 7.G).***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
	E. Does the plant have the potential to change native ecosystems (adds a vegetative layer, affects ground or surface water levels, etc.)?	***No***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
	F. Does the plant have the potential to introduce or harbor another pest or serve as an alternate host?	***No***	**This text is provided as additional information not directed through the decision tree process for this particular risk assessment.**
9	Does the plant species have clearly defined benefits that outweigh associated negative impacts?		
	A. Is the plant currently being used or produced and/or sold in Minnesota or native to Minnesota?	No.	Go to Box 10

Box	Question	Answer	Outcome
	B. Is the plant an introduced species and can its spread be effectively and easily prevented or controlled, or its negative impacts minimized through carefully designed and executed management practices?		
	C. Is the plant native to Minnesota?		
	D. Is a non-invasive, alternative plant material commercially available that could serve the same purpose as the plant of concern?		
	E. Does the plant benefit Minnesota to a greater extent than the negative impacts identified at Box #8?		
10	Should the plant species be enforced as a noxious weed to prevent introduction &/or dispersal; designate as prohibited or restricted?		
	A. Is the plant currently established in Minnesota?	Yes	Go to 10 B
	B. Does the plant pose a serious human health threat?	No	Go to 10 C

Box	Question	Answer	Outcome
	C. Can the plant be reliably eradicated (entire plant) or controlled (top growth only to prevent pollen dispersal and seed production as appropriate) on a statewide basis using existing practices and available resources?	Yes. (still a very subjective break point on path to regulate or not regulate) Biological control agents shown to be effective on musk thistle (*Rhinocyllus conicus*) may attack plumeless thistle, but are not that efficacious on plumeless thistle. In addition to introductions for musk thistle control, *Trichosirocalus horridus* was subsequently introduced to target plumeless control. Control has been shown in Virginia but took 12 years to develop to a control status (Kok 2001). Herbicides are an effective option in non-organic grass systems. Herbicides will cause unacceptable forage legume injury in grass : legume systems (personal observations) but may be warranted where high populations of plumeless thistle have established. Appropriately timed repeated mowing can greatly suppress seed production of musk thistle (Desrochers et al. 1988) and reduced number of capitulum produced in plumeless thistle (Feldman and Lewis 1990), which may meet prohibited control requirements. Grazing management effects on plumeless thistle are not reported specifically, but Renz and Schmidt (2012) provide the most recent insights on grazing effects on invasive thistles. Infestations that have become widespread and dense should be controlled to prevent seedbank driven issues at that site and in the surrounding areas.	LIST THE PLANT AS A PROHIBITED / CONTROL NOXIOUS WEED (eradication not possible or reasonable)
11	Should the plant species be allowed in Minnesota via a species-specific management plan; designate as specially regulated?		

2013

Final Results of Risk Assessment		
Review Entity	**Comments**	**Outcome**
NWAC Listing Subcommittee	First review – 06/20/2013, Final Review 08/12/2013 The subcommittee recommends removing *C. nutans and C. acanthoides* from the noxious weed list because of their lack of significant impact on agriculture, native ecosystems, or human health.	2013 - Delist both Musk and Plumeless Thistle
NWAC Full Committee	First Review 12/18/2013 – Delisting caused quite a bit of discussion among members. It was mentioned by several members that non-native thistles have a significant impact on grazing agriculture, haying, and marginal land profitability. Plumeless thistle was thought to be a much greater problem than musk thistle and was thought to be a species that can freely invade and establish in quality grazing paddocks as well as high- value haying lands and wildlife areas. Musk thistle is thought to be more regional to the SE, SC and SW counties. Musk thistle could be added to County Noxious Weed lists where presumed to be a problem. Plumeless thistle is thought to be too wide-spread of a problem to delist. It is also being reported to displace current musk thistle populations and continues to spread southward from its source populations in northern MN.	MUSK THISTLE – Vote 11 – 2 for delisting PLUMELESS THISTLE - Vote 7 – 6 in favor of delisting
MDA Commissioner	First Review 02/24/2014 - Petition letters received by the commissioner's office from four member organizations overwhelmingly disagreed with NWAC's recommendation for these non-native thistles. The MDA also received other comments regarding the recommendations to delist plumeless and musk thistles that indicated farmers and private landowners alike would be upset if the recommendation was approved – primarily for plumeless thistle. Also, the Farmer's union was unable to attend the voting meeting on 12/18/2013. Had they have been able to vote, they would have voted against delisting thus making the vote a 7 – 7 tie and by NWAC's bylaws that would have made the recommendation for plumeless thistle to remain as a Prohibited-Control Species.	**MUSK THISTLE -** Based on NWAC's majority vote and lack of specific feedback by member groups, **the commissioner accepted NWACS recommendation to de-list, allowing counties to add to their County Noxious Weed Lists**. **PLUMELESS THISTLE** - The commissioner rejected NWAC's recommendation to delist plumeless thistles. **The commissioner has directed that plumeless thistle remain as a prohibited- control species** to

		support the counties and townships opinion, in addition to comments from the Farmer's Union and MN Crop Improvement Association, that any changes would be detrimental to grazing agriculture and potentially cause confusion within the seed industry

2019

Review Entity	Comments	Outcome
NWAC Listing Subcommittee	Second review – 07/2019. The subcommittee recommends maintaining the Prohibited Control designation for plumeless thistle due to the potential for localized, significant economic impact for livestock producers.	2019 - Maintain the Prohibited Control designation
NWAC Full Committee	Vote on 12/03/19 was 15:0 in favor of remaining Prohibited Control.	Prohibited Control
MDA Commissioner	Commissioner agreed	Prohibited Control

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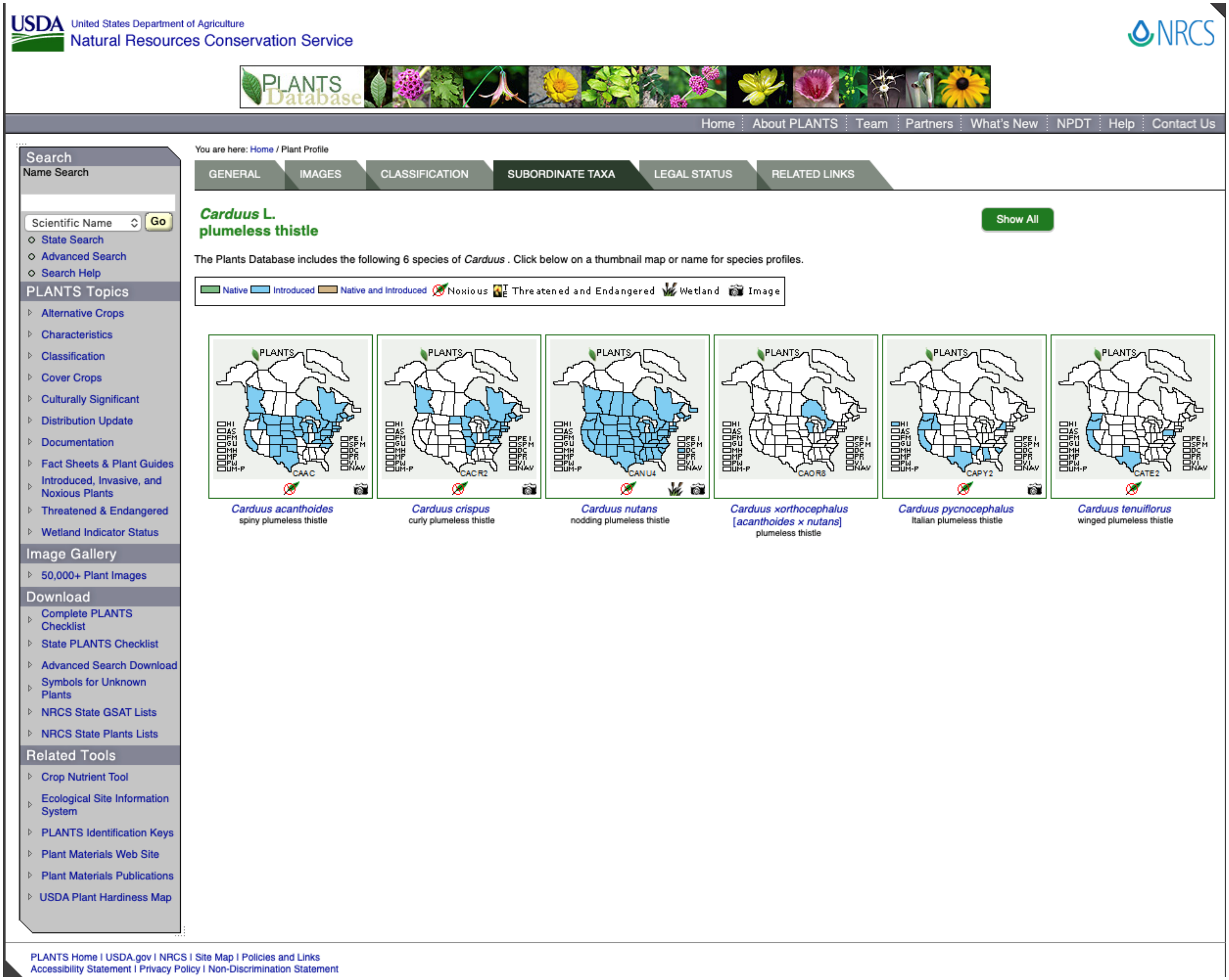

Figure 1. Six *Carduus* species in the U.S. PLANTS. Accessed June 25 2019.

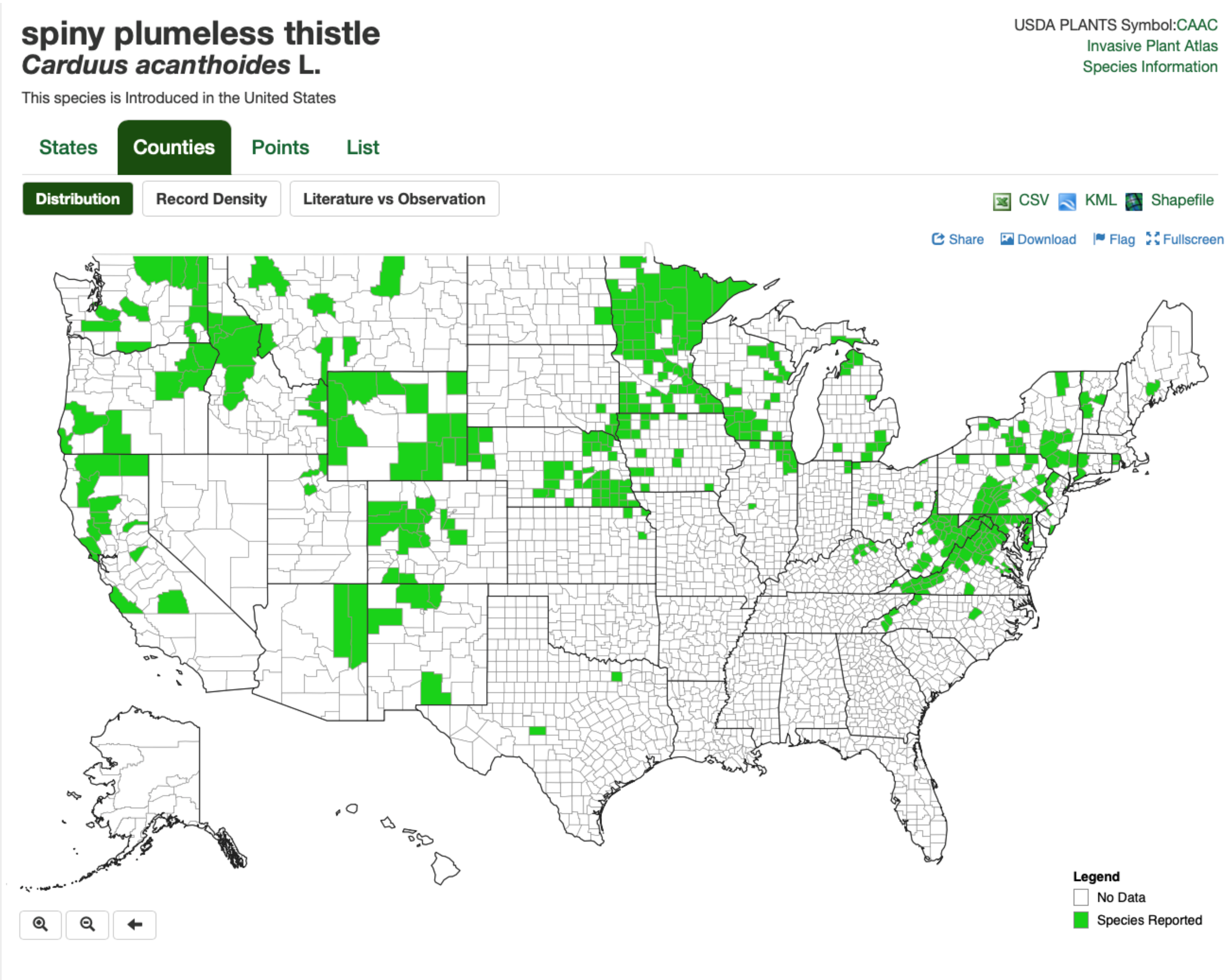

Figure 2. Distribution of plumeless thistle in the U.S. EDDMapS Accessed June 25 2019.

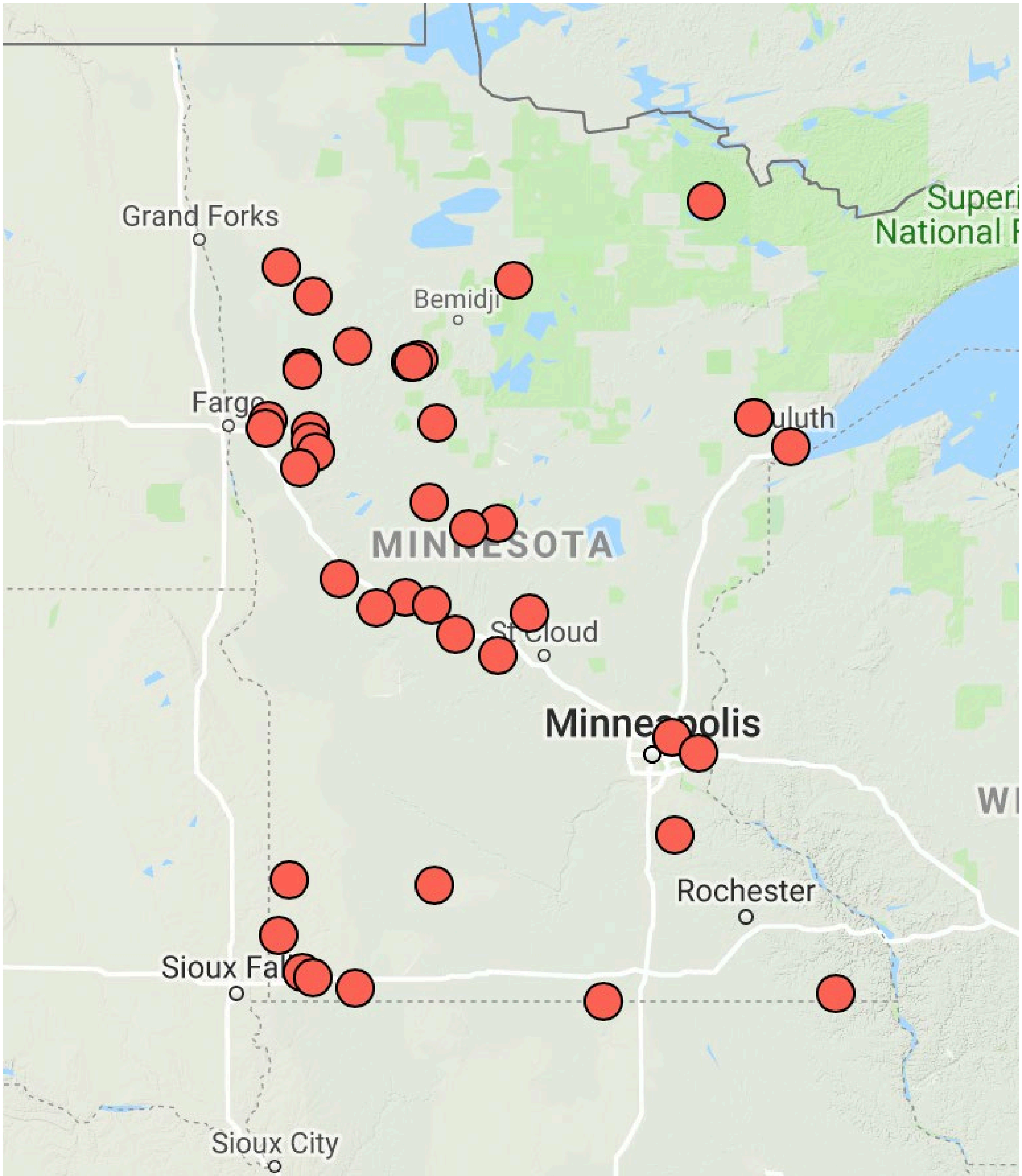

Figure 3. Herbarium records of plumeless thistle in Minnesota. The Bell Museum. Accessed June 25 2019.

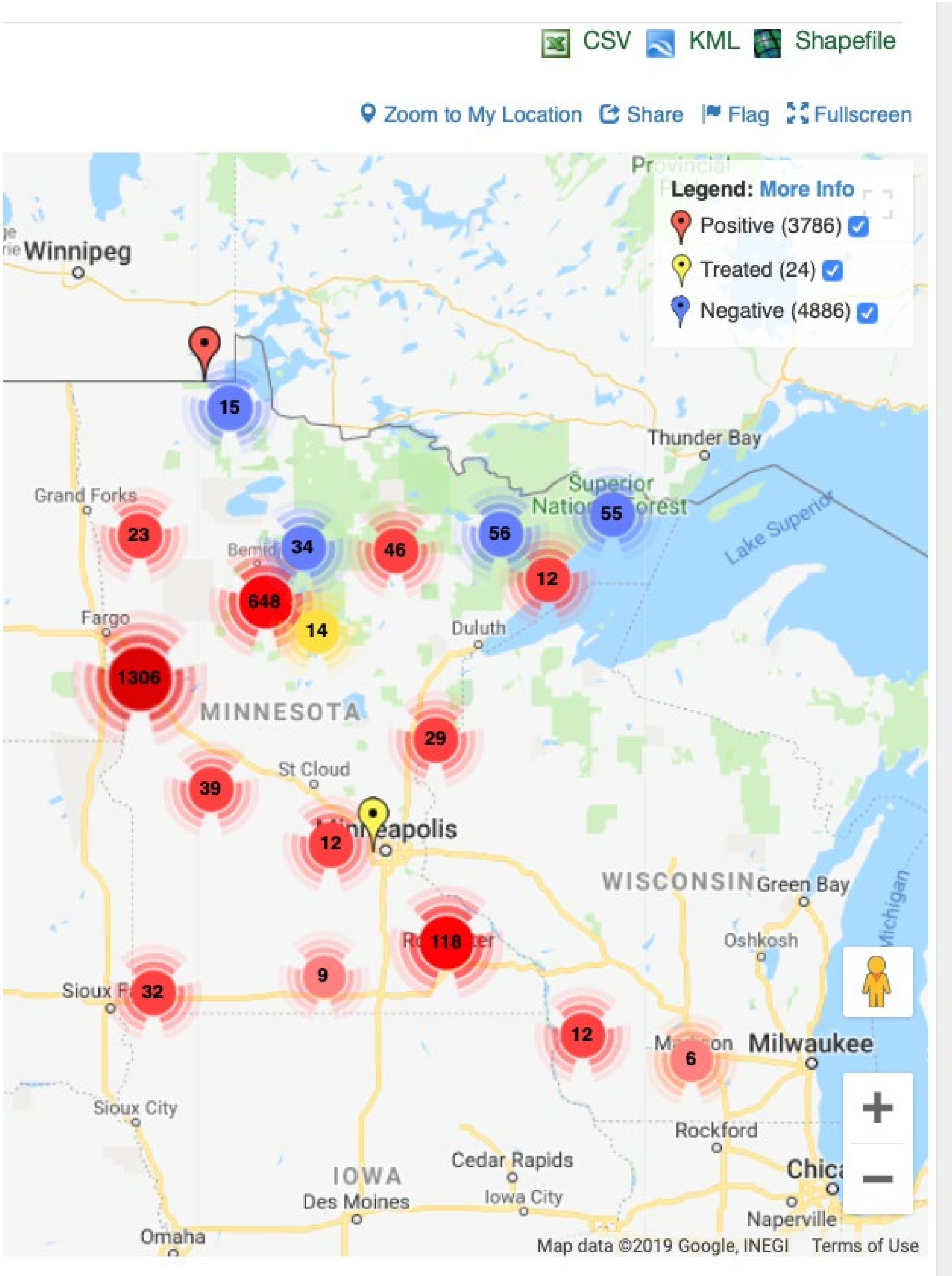

Figure 4. Reports of plumeless thistle in the Minnesota. EDDMapS Accessed June 25 2019.

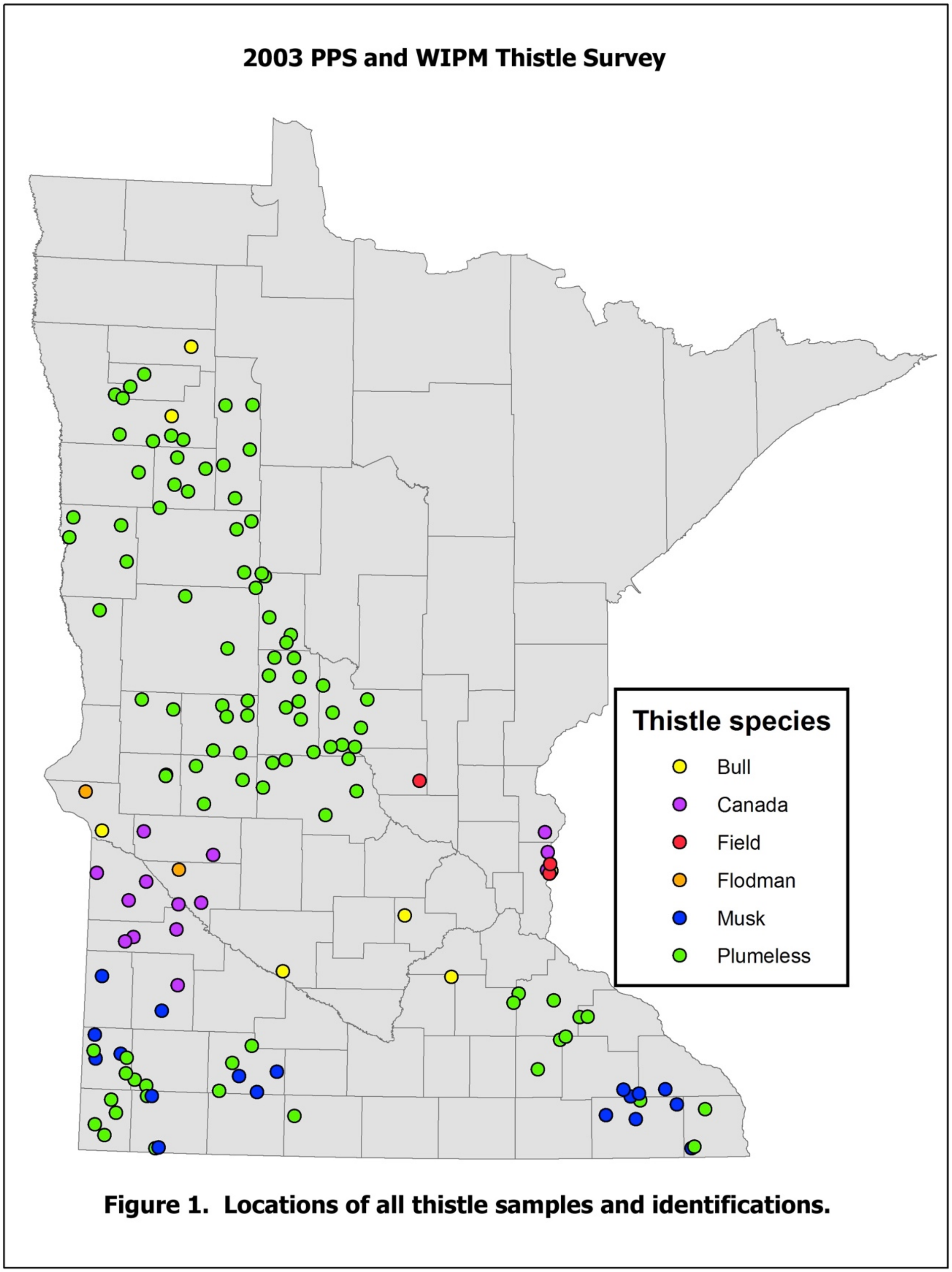

Figure 5. Location of thistle samples recorded as part of the 2003 MDA Plant Pest Survey. (MDA 2003).

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Abstracts of additional Literature, many of which were not cited in the 2019 RA:

Allen, M.R. and Shea, K. 2006. Spatial Segregation of Congeneric Invaders in Central Pennsylvania, USA. Biological invasions. 8:509-521.
Carduus acanthoides and *Carduus nutans* (plumeless and musk thistles) are among the most noxious weeds in the United States of America, presenting a serious challenge in cropping and pasture systems. Unfortunately, a lack of detailed spatial distribution information hampers both our ability to understand the factors affecting their invasive success, and the effectiveness of monitoring and management efforts. To examine patterns of distribution and co-occurrence at a local level, we sampled a 5000 km^2 area of central Pennsylvania that cut a transect across known areas of *C. acanthoides* and *C. nutans* infestation. A number of potential environmental explanatory variables were recorded and analyzed to examine whether they correlated with observed species distribution patterns. Patterns of forest density and spatial aggregation of the thistles were the primary covariates that significantly impacted both species' distributions. The survey established that the frequency of sightings for each species diminished as the ranges converged, with only brief overlap: the two species are strongly negatively correlated in space. Understanding environmental correlates of infestation and the pattern of spatial dissociation of these two invasive species is an important step towards an improved understanding of the mechanisms underlying their invasive potential, and hence towards effective weed control.

Briano, A.E., H.A. Acciaresi, and J.A. Briano. 2013. Establishment, dispersal, and prevalence of *Rhinocyllus conicus* (Coleoptera: Curculionidae), a biological control agent of thistles, Carduus species (Asteraceae), in Argentina. Biological control. 67:186-193.
These results suggest that the direct damage of *R. conicus* on *C. acanthoides* would not be sufficient to substantially decrease seed production and biological control should be complemented with other control techniques, such as mowing and/or the use of herbicides. However, an eventual integrated management should be conducted without affecting either the plant-herbivore interaction at the beginning of the flowering season or the life cycle of the weevil. According to the results reported here, a general recommendation would include the implementation of additional control techniques not earlier than two months after the initial oviposition of the weevil. This way, the complete development of *R. conicus* would be allowed in most of the heads. Similarly, studies on *C. thoermeri* showed that mowing or the use of herbicides after the senescence of the first heads did not affect the development of *R. conicus* (Trumble and Kok, 1979; Kok, 1980; Harris, 1986; Tipping,1991). The fact that *C. acanthoides* is a weed highly dependent of the seed bank accumulated during the previous season (Tipping, 2008) emphasizes the importance of the complementation of the weevil with other control techniques. This pilot damage experiment should be repeated in other areas and with both *C. acanthoides* and *C. thoermeri.*

Jongejans, E., E.J. Silverman, O. Skarpaas, K. Shea. 2015. Post-dispersal seed removal of *Carduus nutans* and *C. acanthoides* by insects and small mammals. Ecological research. 30:173-180.
In cages that allowed insect access, 88 % of the seeds were removed after 1 day, and 99.9 % were removed after the 6-day trial. When insects were excluded, the removal rate was significantly lower (18 % after 1 day, 40 % after 6 days). The seed removal rates provide an upper limit to the seed predation rate, with the understanding that it is also possible for seed removal to be an important secondary dispersal mechanism. We discuss a combined empirical-theoretical approach to evaluate the impact of these alternative seed fates on the spread and management of these thistles.

Jongejans, E., O. Skarpaas, P.W. Tipping, and K. Shea. 2007. Establishment and spread of founding populations of an invasive thistle: the role of competition and seed limitation. Biological Invasions. 9:317-325.
Successful plant invasions require both the founding and local spread of new populations. High plant densities occur only when founding plants are able to disperse their seeds well locally to quickly colonize and fill the new patch. We test this ability in a 7-year field experiment with *Carduus acanthoides*, an invasive weed in several North American ecosystems. Founder plants were planted in the center of 64 m^2 plots and we monitored the recruitment, distribution pattern, mortality, and seed production of the seedlings that originated from these founding plants. Competing vegetation was clipped not at all, once, or twice each year to evaluate the importance of interspecific competition. More seedlings recruited in the intermediate once-clipped plots, and these seedlings also survived better. The control plots had fewer microsites for seedling recruitment; clipping a second time in September stimulated grasses to fill up the gaps. The number of *C. acanthoides* recruits and their median distances from the founder plants were also explained by the initial seed production of the founding plants. Overall, the experiment shows that the success of founder plants can fluctuate strongly, as 55% of the plots were empty by the sixth year. Our study suggests that the local invasion speed following initial establishment depends strongly on both the propagule pressure and availability of suitable microsites for seedling recruitment and growth.

Kok, L T. 2001. Classical biological control of nodding and plumeless thistles. Biological Control..21:206-213.
Nodding (musk) thistle (*Carduus thoermeri* Weinmann in the *Carduus nutans* L. group) and plumeless thistle (*Carduus acanthoides* L.) are introduced noxious weeds of Eurasian origin. Both weeds are problematic in pastures, rangelands, and croplands and along state highways in many parts of the United States. The success of both species of thistles is largely due to their prolific seed production, seed longevity, competitive ability, and lack of natural enemies. Classical biological control of nodding thistle in Virginia has been achieved with three exotic thistle herbivores, *Rhinocyllus conicus* Froelich (Coleoptera: Curculionidae), *Trichosirocalus horridus* (Panzer) (Coleoptera: Curculionidae), and *Cassida rubiginosa* Muller (Coleoptera: Chrysomelidae). *T. horridus* also effectively controls plumeless thistle. These insect herbivores complement each other. Nodding thistle biological control is achieved in about 5-6 years in Virginia, Missouri, and Montana. In addition, a rust fungus (*Puccinia carduorum* Jacky) (Uredinales: Pucciniaceae) has been introduced and established for control of nodding thistle in Virginia. Development and reproduction of the three thistle herbivores are not adversely affected by the rust. The rust hastens plant senescence and reduces seed production. Control of plumeless thistle with R. conicus and T. horridus takes approximately twice as long as control of nodding thistle.

Laterra, P, and M.E. Bazzalo. 1999. Seed-to-seed allelopathic effects between two invaders of burned Pampa grasslands. Weed research. 39:297-308.
The establishment of *Lotus tenuis* can interfere with colonization by *Carduus acanthoides* during the early post-burn recovery of Flooding Pampa grasslands. The purpose of this research was to determine the potential role of L. tenuis seeds as a source of allelopathic compounds involved in that interaction. Imbibed seeds of *L. tenuis* and aqueous leachates from them were bioassayed for their ability to inhibit germination and seedling growth of *C. acanthoides*, both on sterilized filter paper and on pasteurized soil as substrata. Germination and/or emergence of *C. acanthoides* were inhibited and root length was reduced on filter paper or soil, by both the presence of *L. tenuis* seeds and their leachate, at densities of *L. tenuis* near the maximum values observed in the field. Germination and seedling growth of *C. acanthoides* were less affected by the presence of *L. tenuis* seeds than by the addition of their leachate, and the presence of *L. tenuis* seeds or their

leachate showed stronger effects on emergence of *C. acanthoides* from soil than on its germination on filter paper. Methods applied for leachate sterilization, ultrafltration or autoclaving did not modify *C. acanthoides* responses. Neither the germination rate nor the root length of *C. acanthoides* seedlings were affected by solutions of polyethylene glycol with similar osmolarity to the leachates. We conclude that the release of inhibitory substances on to filter paper and into pot soil from imbibed *L. tenuis* seeds would be the mechanism responsible for the observed effects.

Marchetto, K.M., E. Jongejans, K. Shea, and S.A. Isard. 2010. Plant spatial arrangement affects projected invasion speeds of two invasive thistles. Oikos. 119:1462-1468.
The spatial arrangement of plants in a landscape influences wind flow, but the extent that differences in the density of conspecifics and the height of surrounding vegetation influence population spread rates of wind dispersed plants is unknown. Wind speeds were measured at the capitulum level in conspecific arrays of different sizes and densities in high and low surrounding vegetation to determine how these factors affect wind speeds and therefore population spread rates of two invasive thistle species of economic importance, *Carduus acanthoides* and *C. nutans*. Only the largest and highest density array reduced wind speeds at a central focal thistle plant. The heights of capitula and surrounding vegetation also had significant effects on wind speed. When population spread rates were projected using integrodifference equations coupling previously published demography data with WALD wind dispersal models, large differences in spread rates resulted from differences in average horizontal wind speeds at capitulum height caused by conspecific density and surrounding vegetation height. This result highlights the importance of spatial structure for the calculation of accurate spread rates. The management implication is that if a manager has time to remove a limited number of thistle plants, an isolated thistle growing in low surrounding vegetation should be targeted rather than a similar sized thistle in a high-density population with high surrounding vegetation, if the objective is to reduce spread rates.

Rauschert, E.S., S. Jalics, and K. Shea. 2012. Invasional interference due to similar inter- and intraspecific competition between invaders may affect management. Ecological Applications. 22:1413-1420.
As the number of biological invasions increases, the potential for invader-invader interactions also rises. The effect of multiple invaders can be superadditive (invasional meltdown), additive, or subadditive (invasional interference); which of these situations occurs has critical implications for prioritization of management efforts. *Carduus nutans* and *C. acanthoides*, two congeneric invasive weeds, have a striking, segregated distribution in central Pennsylvania, USA. Possible hypotheses for this pattern include invasion history and chance, direct competition, or negative interactions mediated by other species, such as shared pollinators. To explore the role of resource competition in generating this pattern, we conducted three related experiments using a response-surface design throughout the life cycles of two cohorts. Although these species have similar niche requirements, we found no differential response to competition between conspecifics vs. congeners. The response to combined density was relatively weak for both species. While direct competitive interactions do not explain the segregated distributional patterns of these two species, we predict that invasions of either species singly, or both species together, would have similar impacts. When prioritizing which areas to target to prevent the spread of one of the species, it is better to focus on areas as yet unaffected by its congener; where the congener is already present, invasional interference makes it unlikely that the net effect will change.

Russo, L., C. Nichol, K. Shea, and A. Traveset. 2016. Pollinator floral provisioning by a plant invader: quantifying beneficial effects of detrimental species. Diversity & distributions 22:189-198.

Our results suggest that, despite causing significant problems, the invasion of this non-native species may also provide crucial benefits via floral resources for pollinators. Benefits, such as the floral resources that invaders provide to pollinators, should also be taken into account in conservation and invader management plans. Eradication or complete removal of invasive species which provision insects with floral resources could have unintended negative impacts on the associated pollinator community.

Sanderson, M.A., Brink, G., Ruth, L., R. Stout. 2012. Grass-Legume Mixtures Suppress Weeds during Establishment Better than Monocultures. Agronomy journal. 104:36-42.
Maintaining a diversity of plant species in pastures may reduce weed invasion. Knowledge of how the proportion of species in a mixture (i.e., species evenness) affects weed invasion would be useful in formulating seed mixtures. We hypothesized that forage mixtures with greater species evenness would reduce weed invasion at establishment better than mixtures dominated by a few species (low spe- cies evenness) or monocultures. Fifteen mixtures and monocultures of orchardgrass (*Dactylis glomerata* L.), quackgrass (*Elytrigia repens* L.), alfalfa (*Medicago sativa* L.), and white clover (*Trifolium repens* L.) were sown in autumn 2008 at four locations in Pennsylva- nia and Wisconsin. There were four monocultures, four mixtures dominated by one species (evenness = 0.64), six mixtures dominated by pairs of species (evenness = 0.88), and one equal mixture (evenness = 1). We measured the amount of naturally occurring weeds in harvested herbage at each location in 2009. At two locations, we added seed of plumeless thistle (*Carduus acanthoides* L.) and canola (*Brassica napus* L.; a surrogate weed) to each treatment during autumn of 2008 and measured their establishment and dry mass during 2009. Grass–legume mixtures resisted weed invasion better than monocultures. Within mixtures, however, species evenness did not influence weed invasion. Species evenness did not affect resource use (light interception or soil inorganic N levels). Individual forage species had a strong effect because weed proportions decreased curvilinearly as orchardgrass proportion of the seed mixture increased. Selecting appropriate species to use in mixtures is more important than the evenness of the species in the mixture.

Skarpaas, O, R. Auhl, and K. Shea. 2006. Environmental variability and the initiation of dispersal: turbulence strongly increases seed release. Proceedings of the Royal Society B. 273:751-756.
Dispersal is a critical process in ecology. It is an important biological driver of, for example, invasions, metapopulation dynamics, spatial pattern formation and pathogen movement. Much is known about the effect of environmental variability, including turbulence, on dispersal of diaspores. Here, we document experimentally the strong but under-explored influence of turbulence on the initiation of dispersal. Flower heads of two thistle species (*Carduus nutans* and *Carduus acanthoides*) with ripe seeds were exposed to series of laminar and turbulent air flows of increasing velocity in a wind tunnel. Seed release increased with wind speeds for both laminar and turbulent flows for both species. However, far more seeds were released, at significantly lower wind speeds, during turbulent flows. These results strongly suggest a need for more quantitative studies of abscission in the field, as well as dispersal models that incorporate variability in the diaspore release phase.

Skarpaas, O., E.J. Silverman, E. Jongejans, and K. Shea. 2011. Are the best dispersers the best colonizers? Seed mass, dispersal and establishment in *Carduus* thistles. Evolutionary Ecology. 25:155-169.
We applied a mechanistic wind dispersal model (WALD) to seeds released under a range of environmental conditions, and tested germination and seedling growth under standardized conditions in a greenhouse. Dispersal distance and establishment (germination and seedling growth) were not significantly correlated, although in both species smaller seeds dispersed

farther, and showed lower germination and lower seedling growth rates. This apparent paradox can partly be explained by the significant influence of other factors such as release height and environment (wind and vegetation), which explained more variation in dispersal than did terminal velocity. Another potential explanation is the variation in seed traits: germination is strongly positively related to seed mass, weakly positively related to plume loading, but not significantly related to terminal velocity. This weakening of the correlation with germination is due to additional layers of trait (co)variability: for instance, seed mass and pappus size are positively correlated, and thus big seeds partially compensate for the negative effect of seed mass with larger pappi. Our mechanistic approach can thus lead to a better understanding of both potentially opposing selection pressures on traits like seed mass, and diluting effects of other seed, plant and environmental factors.

Zhang, R., J.M. Heberling, E. Haner, Emily, and K. Shea. 2011. Tolerance of two invasive thistles to repeated disturbance. Ecological Research 26:575-581.
Many invasive species have short life cycles, high reproduction, and easily dispersed offspring that make them good ruderal species under disturbance. However, the tolerance of such ruderal species to disturbance is often overlooked. In a 2-year mowing study, we applied frequent intense disturbances to examine the tolerance of two congeneric invasive thistles, *Carduus acanthoides* and *Carduus nutans*, and potential differences in their responses. Our results show that both species can survive multiple mowing events, with *C. acanthoides* surviving repeated intense mowing through a whole season. Furthermore, *C. acanthoides* was found to adjust its growth form to the disturbance regime, and successfully overwintered and reproduced in the subsequent growing season if the disturbance was terminated. Our results support the idea that tolerance to disturbance should be considered when examining invasions by short-lived monocarpic species, since avoidance of disturbance via rapid life cycle completion and seed production, and tolerance of disturbance via regrowth can co-occur in these species. Consequently, management of short-lived invasives should take both life history strategies into account.