Biological Control of Musk Thistle in Kansas

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Biological control involves the use of a pest's natural enemies to reduce its numbers and economic impact. Biological control of weeds makes use of insects, mites, and sometimes, pathogenic microorganisms that are adapted to feeding on particular plant species. In Kansas, as in other parts of North America, the most serious weeds are exotic plants that have invaded from other parts of the world. Therefore, biological control programs begin by searching in countries where the invasive weed originated to locate candidate organisms that have high potential for establishment and for substantially reducing growth and reproduction of the target weed. After careful screening to ensure that nontarget plants are not attacked, one or more natural enemies highly specific to the weed may be imported, mass-produced, and then released. This approach is called importation or 'classical' biological control.

There are many other examples where biological control of weeds has been used with varying degrees of success, including many dramatically successful programs. Despite the documented successes and high benefit-to-cost ratio, funding to support biological control has been meager except in situations where conventional weed management methods are either too costly or logistically impractical. The dual advantages of biological control are that the weed-suppressive agents are *self-sustaining* (they reproduce and persist in the environment without requiring further inputs) and are capable of *dispersal* (they can spread to new areas without human assistance).

This publication describes the current state of biological control of musk thistle in Kansas and is intended to complement publications that address the status of this weed and its introduced natural enemies in other parts of the United States and in Canada. Topics covered include the history of the introduction and spread of musk thistle in the United States and Kansas; description of the weed and its seasonal life cycle in Kansas; history of the biological control program, nationally and in Kansas; biology, seasonal activity, and distribution of the two weevil species established for its control; estimated impact of the biological control program on musk thistle populations; methods for collecting and redistributing musk thistle weevils; practical ways for farmers, ranchers, state agencies and others to work together to document, promote, and preserve musk thistle biological control; and procedures to follow for individuals who wish to participate in the state-approved biological control program.

Origin, Distribution, and Life History of Musk Thistle

Carduus nutans L., commonly known as musk thistle or nodding thistle, is a plant of Eurasian origin that was accidentally introduced to the United States about 150 years ago, likely as a contaminant of crop seed. It was first discovered in Kansas in 1932. By 1992, it had become widely established throughout the state, with almost all counties reporting musk thistle populations. Heaviest populations occur in north central and northeast Kansas (Figures 1a-c). As of 2008, several western counties were reported to have heavy infestations (Figure 1c).

In Kansas, the life cycle of musk thistle varies from a winter annual to a biennial (requiring two growing seasons to reach maturity), but it also has been observed as a summer annual (completing maturity from seed in a single growing season). Reproduction is exclusively by seed. Seeds usually germinate anytime there is sufficient soil moisture, but mostly in late summer, fall, or spring. Seedlings develop into the rosette stage, consisting of a ring of overlapping leaves, which lie flat on the ground. The plant remains in this vegetative stage for the majority of its life cycle.

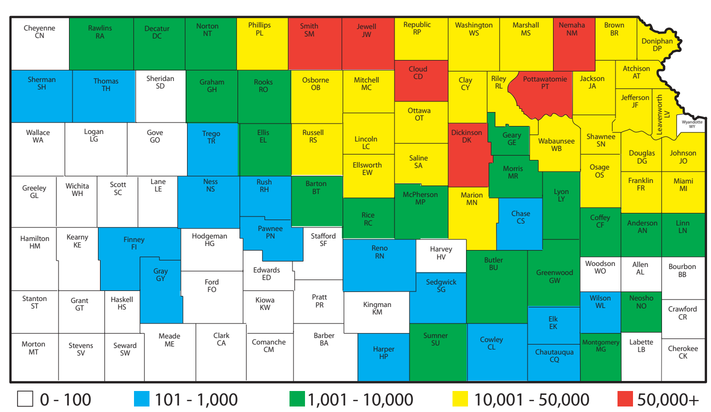

Figure 1a. Musk thistle county distribution, 1991

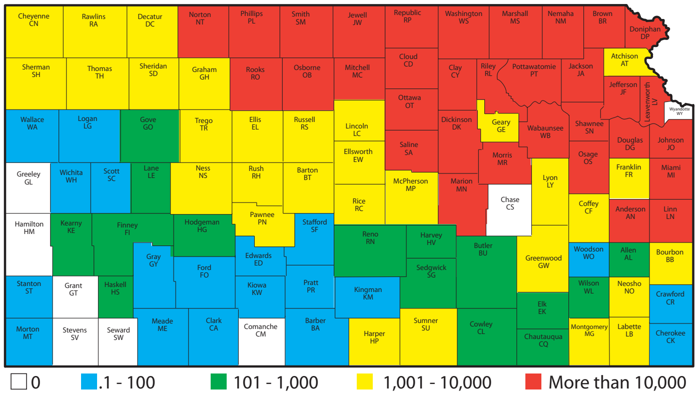

Figure 1b. Musk thistle county distribution, 1998

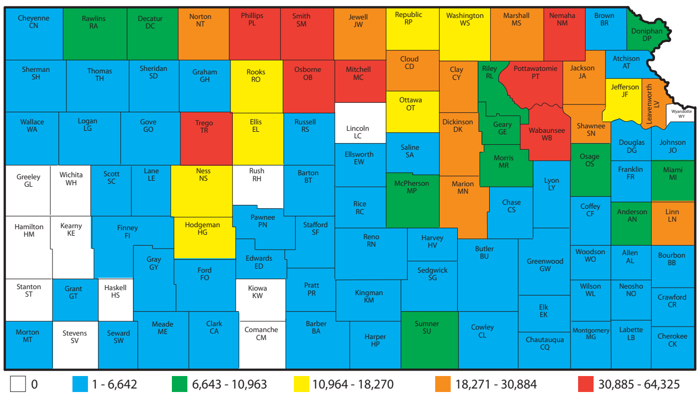

Figure 1c. Musk thistle county distribution, 2008

The bolting stage begins with the formation of an elongated primary seed stalk and continues until flower heads form and seeds develop. Flowers are usually reddish-pink to violet or purple and the plant's branching nature often results in many flowers per plant. Following maturity, the head assumes a fluffy, white appearance as mature seed begins emerging from the head. Seeds are attached to a parachute-like white pappus that facilitates dispersal on the wind. Most seeds fall within 300 feet of the mother plant.

Biological Control Program

Two insects that help control musk thistle in Kansas are *Rhinocyllus conicus* (Froelich), commonly called the **head weevil**, and *Trichosirocalus horridus* (Panzer), commonly called the **rosette weevil**. Both of these weevils are native to Europe and were studied extensively before being released to control musk thistle in the United States.

In 1973, Dr. Ernst Horber, an entomologist at Kansas State University, released *Rhinocyllus conicus* in Riley County near Manhattan. From 1975-78 he made additional releases of head weevils in a total of seven counties. In 1979, employees of the Kansas State Board of Agriculture, in cooperation with the County Weed Directors Association of Kansas, Horber, Kansas State University, and the KSU Cooperative Extension Service released the head weevil in approximately 50 counties throughout Kansas. Establishment did not occur at many of the release sites for a variety of reasons, but *R. conicus* did become established in several counties in north central and northeast Kansas. Subsequently, head weevils spread naturally to thistle-infested areas in adjacent counties.

Trichosirocalus horridus was first released in 1978 near Manhattan by Horber. He released it again in 1982. By 1989 rosette weevils were established well enough in isolated locations to allow for modest collecting and redistribution. In 1989, a large-scale collection and release program for both weevils was initiated by the Plant Health Division of the Kansas State Board of Agriculture and the County Weed Directors of Kansas. The weevil redistribution program continued through 1992.

Weevil Distribution in Kansas

Counties where head weevils (Figure 2) and rosette weevils (Figure 3) were released and became established are shown below. The head weevil is more widely distributed than the rosette weevil. Part of the difference in distribution may be that the head weevil was released almost a decade earlier than the rosette weevil. It is also more likely that head weevils are better adapted to a wider range of the environmental conditions encountered in Kansas than are rosette weevils. Currently, head weevils are established throughout most of the state. The rosette weevil is restricted to northeast Kansas. Its range has expanded very little over the past 15 years.

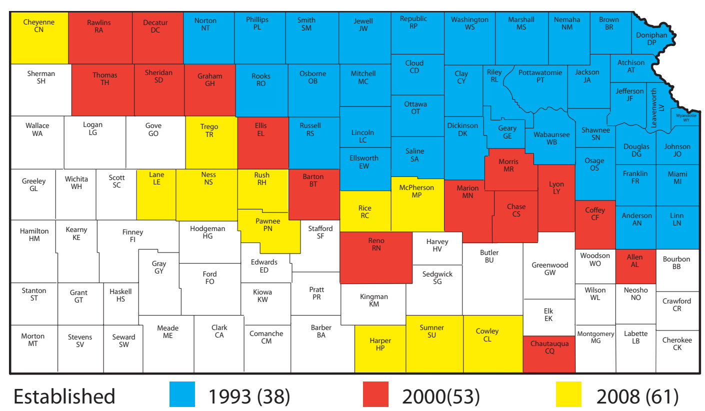

Figure 2. Head weevil county distribution, 1993 – 2008

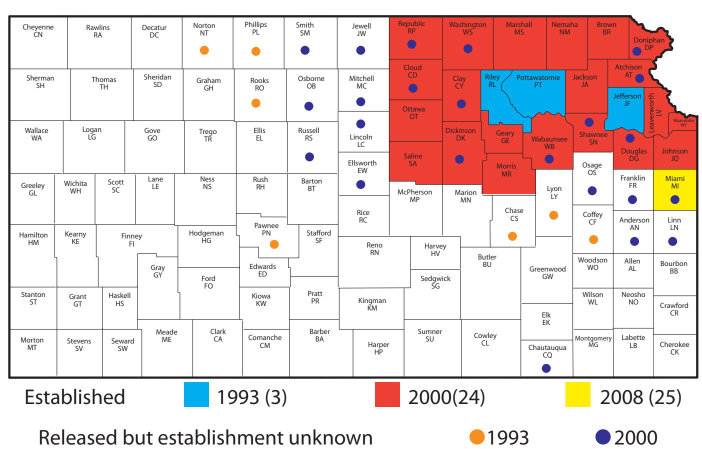

Figure 3. Rosette weevil county distribution, 1993 – 2008

Biology and Life History

Figure 4. Adult head weevil, *Rhinocyllus conicus*

Figure 5. Musk thistle flower head showing head weevil egg masses

Figure 6. Mature flower head showing head weevil larvae inside

Head weevils overwinter as adults (Figure 4) emerging in the spring to congregate on musk thistle plants during the bolting stage. Adults feed and mate, then lay eggs on the bracts of flower buds, singly or in clusters. Eggs are covered with a secretion that becomes brown or tan and appears warty or scale-like (Figure 5). Each female will lay between 100 to 150 eggs. Although most egg-laying occurs on terminal buds, eggs may be laid on the stems and secondary buds when infestations are heavy. Cool weather can extend the egg-laying period, while extremely hot weather will decrease it.

Eggs hatch in six to nine days, and larvae immediately burrow into the base of the flower and begin feeding on the ovaries and surrounding tissue, reducing the reproductive potential of the thistle. Larvae are small, creamy-white, legless grubs. They remain in the flower, feeding for 25 to 35 days until fully developed (Figure 6). They pupate within a special cell carved out in the flower head over a period of eight to 14 days. Many larvae congregate in one head; the more larvae per head, the fewer seeds that are produced.

Adults may remain in the cells for up to two weeks, changing color from cream to almost black. Newly emerged adults are about a quarter-inch long. They are generally black, mottled with numerous yellowish-white blotches. Their bodies are noticeably elongate, and they possess a short, blunt snout with antennae attached. In Kansas, adults may emerge from mid-July through mid-August. They seek shelter to overwinter, such as ground litter, wooded areas, and the base of plants. They remain there until the following spring, usually producing one generation per year.

Rosette weevil

Figure 7. Adult rosette weevil, *Trichosirocalus horridus*

Rosette weevil adults typically appear between May and June as they emerge from pupal cases in the soil. Rosette weevil adults are reddish-brown, changing to dark brown or black, with a somewhat mottled appearance that helps distinguish them from head weevils (Figure 7). They are more robust and less elongate than head weevils, with bodies slightly longer than wide. They also have a moderately long and slender beak. After light feeding on the host plant, newly emerged adults seek sheltered habitat, such as ground litter, where they spend the hot summer months. During this dormant period, the weevils do not reproduce or feed.

Figure 8. Split crown showing rosette weevil larvae

As temperatures drop in the fall, adult females emerge from summer resting places, mate, and begin to lay eggs in leaf midribs on the undersides of leaves of thistle rosettes. One female may lay as many as 800 eggs. Eggs laid in early fall will hatch by late fall; however, eggs laid in late fall and early winter may not hatch until the following spring. Consequently, the rosette weevil may overwinter as egg, larva, or adult. Overwintered adults continue to lay eggs through early spring, with the majority of eggs laid during that time. Upon hatching, larvae begin feeding within the midrib and soon migrate toward the center of the thistle rosette (Figure 8). Continued feeding by larvae causes a blackened area of dead crown tissue, commonly referred to as 'deadheart' (Figure 9). As they reach maturity, larvae leave the plant and pupate in the soil. Pupation requires 12 to 20 days depending on the temperature.

Weevil Impact

Head weevils are consistently abundant at most thistle-infested sites in eastern Kansas and in many other parts of the state. They infest a high percentage of flower heads

Figure 9. Dead tissue at center of rosette is called 'deadheart'

beginning in late spring as soon as floral buds are available. Egg-laying continues until about mid-June when they stop producing eggs. But musk thistle plants may continue to produce flower heads for a variable period, depending on seasonal rainfall and temperature. During cooler, rainier summers, new thistle heads may be produced for an extended period after weevils have stopped laying eggs.

In contrast to the head weevil, rosette weevil populations are generally much lower. Based on observations made over many years by KDA personnel, rosette weevil numbers fluctuate but are found at low levels in about 8 of every 10 years. One hypothesis for the generally low rosette weevil populations is that they suffer high winter mortality. Periods of extreme cold weather associated with little or no insulating snow cover are common throughout Kansas. Rosette weevil populations may be higher, for example, in Oklahoma, which has milder winters than Kansas.

Experimental Evidence

Historically, the biological control program for musk thistle in Kansas has been considered a success based on evidence of establishment and high infestation levels, mainly of head weevil. This assumption has been supported by accounts from farmers, ranchers, and state and county personnel of extensive, dense stands of musk thistle before the release of weevils and subsequent observations of reduced densities and coverage. But other factors such as more extensive use of better herbicides and improved land management may have also contributed. Data are lacking that would directly link weevil presence and abundance with reductions in musk thistle populations, which occur over a number of years. The first field experiments that directly measured the impact of the two weevils were conducted in the late 1990s and early 2000s at K-State by Lindsey Milbrath under the direction of Dr. Jim Nechols. Over a three-year period, Milbrath evaluated the role of each weevil separately as well as their combined impact. The goal was to determine whether redistribution of the less-widespread rosette weevil to areas infested only with head weevils could improve biological control.

This field study provided some important insights into weevil impacts on musk thistle in Kansas. First, head weevils reduced viable seed production by about 45 percent on average, despite the fact that thistles continued to produce flower heads beyond the head weevil egg-laying period in all three years. Second, in two years when rosette weevil populations were low, thistles grew to normal height and flower head production was not reduced. This suggests that there are many years in eastern Kansas when rosette weevils may not contribute much to the biological control of musk thistle. But in the third year of the study when natural populations of rosette weevils were higher (about 65 to 70 larvae per plant), musk thistle growth was altered. Multiple flower stems were produced in response to the destruction of initial buds and these were shorter than the primary stems of uninfested plants (Figure 10). More importantly, plants heavily infested with rosette weevils produced fewer flower heads, which means less viable seed. In rare years when rosette weevil densities exceed 70 larvae per plant, rosettes may be destroyed, but this is uncommon.

Figure 10. Multi-stemmed musk thistle plant caused by bud destruction from rosette weevils

In Oklahoma, in some fields where rosette weevils are established, there have been reports of thistle death in the rosette stage or damage at such high levels that no flowering occurred. Whether these impacts are related to rosette weevils at population levels higher than have been found in Kansas is unclear because weevil counts were not recorded. It is also possible that some or all of the added impact on musk thistles was caused by heat or drought stress, but this, too, is inconclusive.

When both weevils occurred together at high densities in northeast Kansas, their combined impact was greater than when only head weevils were present (59 percent versus 45 percent seed reduction). These results suggest that the two weevils may provide enhanced biological control via their additive impacts, although this may happen only occasionally in Kansas. The average impact on seed production from one or both weevils was about 50 percent based on three field seasons. Assuming these results provide a good estimate of average long-term impact, at least half of the viable seed — around several thousand seeds for a vigorous plant — will be deposited in the seed bank, remaining dormant in the soil for a number of years. So an important question is whether there is enough viable seed at any given time to cause future musk thistle outbreaks if conditions become favorable — for example when established vegetation is disturbed or overgrazed.

Apart from the direct impact that weevils have on seed set, an equally important biological control benefit may be to reduce musk thistle's competitive ability with other vegetation. For example, by creating shorter plants with more branches, rosette weevils may enable grasses and other vegetation to outcompete established thistle plants. In addition, shorter thistles may disperse seed over shorter distances, which may reduce the spread of seed to newly disturbed areas.

The individual and combined impact of head and rosette weevils on musk thistle is difficult to predict because existing experimental data apply only to a limited area of northeastern Kansas. It is likely that weevil populations and thistle vigor and productivity will vary throughout the state, and these differences will result in different levels of biological control. On a broader geographic scale, differences in weevil impact in different states can be expected. For example, in Oklahoma the impact of musk thistle weevils — in particular, the rosette weevil — may be greater than in Kansas because of climatic differences affecting weevil and musk thistle populations. This suggests additional observations and experiments are needed.

Surveys for Weevil Presence

Programs to redistribute musk thistle weevils are costly and should not be considered without first determining whether weevils are present. Where they do occur, information on weevil abundance is useful because it helps to identify target areas for possible redistribution and impact assessment and may contribute to a better understanding of geographic differences in weevil distribution and impact. Current distribution maps, although helpful, almost certainly underestimate the zone of establishment of both weevils in Kansas and provide no information on relative abundance or the area infested. The most efficient way to obtain information about weevil activity is a grassroots approach involving farmers, ranchers, and government workers who live and work in counties where assessment is needed. Contributors should know how to recognize each weevil and how and when to examine plants.

Detection

To detect head weevils, it is best to look on the bracts of flowers for the tannish egg masses that persist on the flower heads for many weeks (Figure 5). Flower heads can be split and examined for cream-colored larvae (grubs) to reveal the stage of population development, but is not necessary for diagnosing infestation. Adults of the rosette weevil can be found by examining the undersides of the leaves on flattened rosettes before bolting. Newly-emerged adults may also be found on bolted, flowering plants in May and June. Indirect indications of rosette weevil presence are the presence of rosettes with blackened centers where larvae have bored and killed the terminal bud (Figure 9). Plants with multiple stems that are somewhat shorter than the single primary stem of uninfested plants are also signs. This occurs when the apical bud has died and secondary buds develop, but because there are other possible causes for this, further examination is needed. Digging into the crown of the plant and splitting it open may expose larval tunnels and possibly rosette weevil larvae, depending on the time of the year (Figure 8).

Estimating Distribution and Abundance

To evaluate the extent of infestation and relative abundance of head and rosette weevils, infestations of musk thistle should be mapped at different sites within the county and then examined for signs and symptoms of weevils. It is also helpful to estimate the approximate number of plants or the area covered by the thistle infestation because weevils depend on weed abundance — the more thistles, the greater the chance of weevil presence.

At each site, a number of plants should be examined — enough to compute a reasonable percentage infestation for each weevil or to be satisfied that it is absent. If the area involved is small, all plants can be examined, but if the area is large with musk thistle scattered throughout, sampling should be done to cover the most ground with the least effort necessary to permit a good assessment. This is usually accomplished by walking along one or more straight lines (transects) across the entire field, examining thistle plants along the way. If the stand is sparse, all plants within an arm's reach of the transect may be sampled. If the field is large, divide it into evenly spaced zones with at least two transects across it. If there are many thistle plants spread over a large area, a fixed proportion of plants can be sampled along each transect (e.g., every other plant, every fifth plant, etc.).

The objective is to sample a reasonable number of plants (20 or more, depending on the area covered) to get a representative sample of weevil presence. It is also useful to estimate the relative abundance of each weevil. For head weevils, abundance can be estimated as the percentage of infested flowers (the percentage of heads with one or more weevils in any life stage). In addition, a count of the number of egg masses per flower will give the egg mass concentration — or how heavily infested different flower heads are. For rosette weevils, dig the plant out at the crown, split it open, and then count the number of larvae inside. The best time to do this is in mid to late spring when larvae are still developing, but before they have exited the plant to pupate in the soil.

Implementing a Biological Control Program

In 1987, the Kansas State Board of Agriculture (now the Kansas Department of Agriculture) established guidelines for farmers and ranchers who were interested in using weevils for musk thistle biological control. Both weevil species were once available for mail order purchase, but changes in federal regulations now prohibit their transport across state lines, although not their redistribution within states. In 2006, KDA outlined "an official musk thistle control program" in section 4-8-27 of Kansas Administrative Regulations. Landholders wishing to release or redistribute weevils in Kansas must now generate a biological control plan in consultation with their county weed control director. The plan must meet specific criteria outlined in section 4-8-41 and be approved by KDA. Only then will the applicant receive a specific exemption from requirements to implement other control measures within the area covered by the biological control plan. The plan must provide for the maintenance of a continuous thistle-free border at least 150 feet wide around the perimeter of the release area by conventional means (approved cultural or chemical controls). The required width of the border will be determined by the county weed director who will consider factors such as the prevailing wind direction during June and July, the presence of shelter belts and tree lines, the slope of the terrain, the density of the musk thistle population, and the number of weevils that should be released.

Herbicide treatments within the release area are permitted, as needed, only between the dates of October 1 and April 15. Hay cannot be removed from the biological control area unless it has been deemed to be musk thistle-free by the county weed director within the seven days before harvest. Failure to comply with these criteria may result in the biological control plan being revoked, obliging the participant to revert to conventional control measures in order to remain in compliance with noxious weed control obligations.

Choosing a Release Site

There are a number of factors to consider in choosing a good site for releasing musk thistle weevils. Plant density is critical; a minimum of 1,000 plants per site is preferred. Available moisture is a factor that may improve short-term survival, especially for rosette weevils, thus increasing chances of permanent establishment. Sites near a pond or creek are most desirable. Areas with minimal disturbance also favor weevil establishment and population increase. Thistle plants should not be mowed, cut or sprayed for at least two years following any release, and an even longer period is preferred. Cattle should not be allowed to graze in the area, especially during egg-laying periods. Areas that minimize chances for seed dispersal should be considered whenever possible. A creek bottom, deep brushy draw or bluff that will prevent the long distance spread of viable seeds is ideal. Such sites also provide some protection from the severe weather conditions that can exacerbate weevil overwintering mortality.

Collecting Weevils

Spring is the best time to collect head weevils for release. Adults are easier to gather after the thistle plants begin bolting and mated females capable of laying eggs immediately after release are abundant at this time. Research suggests that establishment is 25 times more likely with spring-released weevils than with those released in late summer. But if weather or other factors prevent spring collection, this may be done mid to late summer before adults emerge from the seed head. Newly emerged **rosette weevil** adults do not appear until late spring or early summer, and rarely before bloom, but they remain on plants for some time before entering summer resting places. Rosette weevils are usually abundant on plants during seed development, but as weather becomes hotter in mid-summer, they disperse to seek shelter from the heat and to avoid desiccation, remaining dormant until fall when thistles have germinated and new rosettes are available. Collection in fall is more difficult than in spring because plants are in the small rosette stage. Figure 11 shows the equipment needed to collect and distribute weevils: (A) large plastic or aluminum pan (wash, pie or cake), (B) aspirator, (C) insect sweep net, (D) one pair of leather gloves, (E) 1-pint cardboard carton (e.g., ice cream), (F) insulated ice chest, (G) freezer packs or ice, (H) plastic bag, a large bucket, and a 3-foot long beating stick (not shown).

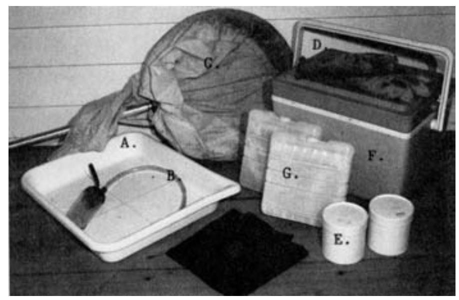

Figure 11. Equipment commonly used to collect head and rosette weevils

Head weevils are best collected on warm, sunny days when the adults are on the upper portions of bolted thistle plants. Thistles in the bolting stage, one to two feet tall, are best for efficient collection. With stick in hand, carefully bend the plant over the sweep net or bucket and gently tap it with the stick (Figure 12). Leather gloves are advisable to protect hands from the sharp thistle spines. You can also tie a plastic garbage bag to your belt and carefully bend the plant into the bag and shake it. Since weevils have a habit of playing dead when disturbed (a behavior known as 'thanatosis'), tapping or shaking causes them to drop into a net, bucket or bag.


Figure 12. Dr. Ernst Horber collecting weevils for redistribution

Once 50 to 100 weevils have been collected, dump them into the pan in a shady spot to keep the weevils cool and prevent them from flying away. Take the aspirator and aspirate the weevils (suck on the tube to draw the weevils into jar of aspirator) leaving other insects and spiders in the pan. Repeat this process until you have collected approximately 500 weevils, place them with some insect-free thistle buds or leaves in the cardboard carton, and seal the lid tightly. Plastic cartons should not be used because they do not 'breathe' and condensation of moisture inside will cause weevil mortality. Place the cartons in the ice chest and keep them cool until the weevils are released. This should be done as soon as possible to ensure that eggs will be deposited at the release site rather than in the carton. Before collecting seed heads in the late summer, cut open a few to see if adult weevils are still within them. Infested seed heads will appear lumpy or bushy with the pappus (long whitish hairs) still attached to the developed weevil cell. An uninfested head will appear smooth with all the pappus gone. To collect infested heads, pull off the heads and place them in a container, bag, net, or bucket. When approximately 500 weevils have been collected, place them in a cooler and transport them to the release site as quickly as possible.

Optimum collection conditions for the rosette weevil occur from late spring to early summer when the newly emerged adults are crawling around on large thistle plants. This is about four to six weeks after the optimum period for head weevil collection. Collection and handling procedures are the same as for the head weevil unless they are gathered in the fall. At that time, adults can be aspirated directly from the leaves of the thistle rosettes.

Release Methods and Monitoring

Each release site should receive a minimum of 500 adult head weevils. If more can be released, this will decrease the time required for establishment and thistle control. Sprinkle the weevils over the plants at a rate of 5 to 10 per plant; the weevils will disperse by themselves. When releasing rosette weevils, each site should receive a minimum of 150 to 200 adults, distributed in the same manner as the head weevil. Accurate records of release dates and numbers of weevils are desirable, and release sites should be monitored for several years. Record the location of the release site and monitor it regularly for weevil activity. Various environmental factors will determine the weevil population growth and it may take several years for weevils to attain numbers sufficient to suppress the thistle population. Regular monitoring should document weevil presence, relative abundance, and changes in the extent of the thistle infestation.

Weevil Conservation Through Integrated Thistle Management

Although current information suggests that head and rosette weevils are having an impact on musk thistle in at least some areas of the state, it is clear that an integrated management approach that employs supplemental control tactics will be necessary for the foreseeable future, or until additional, and more effective, biological control agents can be introduced. But to protect the weevils that are established, and to retain the biological control benefits associated with them — which are virtually cost-free — herbicide applications and mechanical weed control should be conducted at times that are least disruptive to weevil populations. Figures 13 and 14 show the time of year when musk thistles should, and should not, be removed by other means. In general, spring cultivation and applications of herbicides should be avoided because both weevils are reproducing and developing on thistles at this time. Once adult and immature weevils have left plants, removal of flower heads or entire plants can be done without risk of disrupting their populations. The period from about mid-July to September (Figure 13) is the safest to control musk thistle because both weevils are dormant. A compromise is to use chemical or mechanical control in fall or winter as rosette weevils lay few eggs during that time and head weevils are not present on thistles. Unfortunately, the recommended times for thistle removal do not match times when most herbicides are applied — spring. For this reason, having an approved biological control plan with a designated protected area for thistles and weevils may offer the best opportunity for maintaining healthy populations of biological control agents.

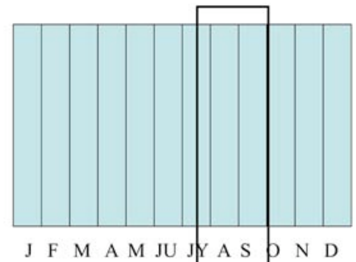

Figure 13. Removal of musk thistles from mid-July to late September has the least negative impact on biological control because neither weevil is active on or in the plants.

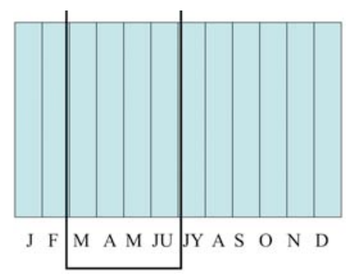

Figure 14. From March through June both rosette and head weevils are actively developing inside plants. Musk thistle removal during this time is the most disruptive to their populations.

Future Considerations

Evaluating Weevil Impact Across Kansas

At present, understanding of the impact of weevils on musk thistle in Kansas derives from limited data obtained in the eastern part of the state. Documentation of weevil infestation levels, seed production, and long-term thistle populations in other parts of the state is needed because of geographic variation in seasonal temperatures and moisture that affect both thistle populations and the efficacy of the biological control agents.

Additional Biological Control Agents

Besides *R. conicus* and *T. horridus*, several other biological control agents have been imported and approved for release against musk thistle in parts of the United States and Canada. A gall-forming fly, *Urophora solstitialis* (L.), was established in Canada more than 20 years ago and was also released in Maryland, although it failed to establish. A stem-boring fly, *Cheilosia corydon* (Harris), was released in Maryland, Texas, Montana, and Oregon but apparently has not established in any of these states. A flea beetle, *Psylliodes chalcomera* (Illiger), that feeds primarily on leaf and flower buds, was released in Texas and Kansas, but without success.

Before approving the release of additional musk thistle-feeding insects in Kansas, it is important to carefully evaluate possible negative outcomes. Besides ensuring that new biological control agents will not feed on non-target plant species, including economically important ones, research is needed to verify that any new insect species will not compete with the head or rosette weevil in ways that will *reduce* the overall level of biological control rather than improve it.

For example, the study by Milbrath and Nechols in eastern Kansas documented that heavy infestations of rosette weevils, while reducing weed productivity, also reduced head weevil numbers through indirect competition. Production of head weevil adults was reduced by more than 60 percent even though the two weevils occur at different times of the year and on different parts of the plant. Fortunately, the impact of the large numbers of rosette weevil appears great enough to compensate for loss of seed consumption by head weevils. Thus, the present challenge is to find new agents that act in concert with the established weevils to reduce thistle productivity, without causing competitive interference.

Summary

At present, head weevils — sometimes with the assistance of rosette weevils — are reducing viable seed production of musk thistle in Kansas by about half, depending on the specific location. Although weevils are contributing enough that steps are warranted to ensure their conservation, good land management practices are still required to achieve acceptable levels of musk thistle control. Preventing the disturbance and exposure of large soil surfaces will enable desirable perennial plants to better compete with musk thistles, with weevils perhaps contributing supplemental suppression. Even then, herbicides and mechanical weed control methods will be required in many areas. However, conventional weed control measures should be carefully timed to minimize their impacts on these established biological control agents.

Acknowledgments

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