ESTABLISHMENT AND IMPACT OF THE MUSK THISTLE HEAD WEEVIL, *RHINOCYLLUS CONICUS*, AND THE ROSETTE WEEVIL, *TRICHOSIROCALUS HORRIDUS*, FOR CONTROL OF MUSK THISTLE, *CARDUUS NUTANS*, IN OKLAHOMA

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PREFACE

Chapter 1 of this thesis is a literature review and introduction to musk thistle, *Carduus nutans* (L.), biology and biological control. Chapters II, III, and IV are manuscripts of the research I conducted during my M.S. program. They are formatted in compliance with the publication policies and guidelines for manuscript preparation with the appropriate journals.

I want to thank my advisor, Dr. Gerrit Cuperus, for giving me this opportunity. His encouragement has helped me put the puzzle pieces together when they made no sense. I also thank my committee, Drs. Phil Mulder, Jim Stritzke, and Mark Payton for all their help and encouragement. Phil, thanks for all the grammar corrections. To my lab helpers, Tererai Nyamanzi, Audrey Sheridan, and Penny Potter, thank you for processing thousands of thistle heads. Very special thanks go to Mr. Leroy Buller who allowed me access to his property and helped me in so many ways. Also thanks goes to Dr. Wright and everyone in the Entomology Department for help, and encouragement.

The biggest thanks is for my husband Rich, you loved and encouraged me all the times I wanted to give up. You were right honey, I am too stubborn to quit. Thank you a thousand times.

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Chapter 1

Literature Review

Musk Thistle History in the United States

Musk thistle, *Carduus nutans* (L.), is an exotic thistle causing serious problems for landowners, managers and environmental specialists. As a highly competitive plant, it is able to compete well with other plants in an area, reducing values of fields and pastures and the crops they produce. One *Carduus* plant on 1.49 m^2 (6711 plants/ha) can reduce pasture yields by 23% (Trumble and Kok 1982) by competing for space, light, and nutrients. Control of this weed has been a priority for many farmers, producers, and Extension Educators.

During the1850's, musk thistle was accidentally introduced from Europe. Its native home includes Mediterranean and Eurasian areas. The most likely means of introduction was via immigrant ships from Europe. It came into the U.S. either as seed contaminating the ballast soil from ships or with unclean seed carried by the immigrants. The earliest recorded sighting is from Pennsylvania in 1853 (Rees 1991). Spreading rapidly across the nation, it was quickly identified as a problem. Musk thistle easily invades poor soils, overgrazed or thin pasture areas, roadside ditches, waste areas and crops (Medd and Lovett 1978b). Sharp spines cover the entire plant, making it unpalatable to cattle (Rees 1991). Heavy infestations can cause large pasture areas to be taken out of production.

In House Bill 1048 (1999),Oklahoma has given musk thistle noxious weed status. This bill gives counties authority to control thistle when the landowner does not provide adequate control. In 1999, 21 of the 48 contiguous states reported the presence of Musk thistle to the National Agricultural Pest

Information System (NAPIS) (NAPIS 1999).

Multiple factors make thistle control difficult. Musk thistle has a large seed load with terminal flowers capable of producing in excess of 1,000 seeds (Beck et al. 1990). Estimated seed counts from large, undamaged plants have exceeded 25,000. Seeds survive for many years in the underground seed bank (Jackman 1999) providing a continuing source of infestation. Transfer of seed to new areas is accomplished via wind, contaminated hay, feed products (Desrochers et al. 1988), small animals, birds, (Rees 1991) and waterways (Stritzke et al. 1999). Farmers have also testified that they have seen farm implements transferred to new areas with musk thistle plants caught in the equipment (Personal Communication).

Herbicide application is often difficult. Timing is critical, with the greatest effect achieved by spraying rosettes during late fall or early spring before plants bolt. Improperly timed applications (once flower heads have formed) do not stop most seed production and has little effect on plant growth (Monks et al. 1991; McCarty and Hatting 1975).

Producers are concerned about crop damage from spray drift, and use it as a reason to reduce chemical input. The herbicide 2-4,D is one of the most commonly recommended chemicals used alone or in combination with others, to control musk thistle (Oklahoma Cooperative Extension Service 1999). Drift from ester formulations of 2-4,D causes serious damage to many sensitive crops (e.g. cotton). Sulfonylureas (metasulfuron), have very serious drift problems affecting cultivated cash crops like corn or cotton (Anderson 1996).

Restrictions on land and harvested-feed use after herbicide application can be problematic for growers. The length of time for feed and harvest restrictions depends on which chemical is used, and intended use of the land or feed removed. Restrictions on use of sprayed feed plants can range from zero days to 70 days for harvested hay fed to lactating cattle (Oklahoma Cooperative Extension Service, 1999).

Some Oklahoma farms have a topography that limits usage of spray equipment. These pastures and ranges are hilly, rocky, or contain a large number of trees and brush. At times, land value itself is so low that additional herbicide costs are not justified (Jackman 1999).

Mowing bolted musk thistle causes a robust plant to produce multiple lateral shoots, instead of only one shoot, with a larger bloom load than the original plant. The plants also carry enough reserves in their tissues to provide for seed maturation once bloom has begun even when the plant top has been severed (McCarty and Hatting 1975).

In the late 1960's, taking the above reasons into consideration, a need for new control measures was identified. Herbicides were able to control the thistles in some circumstances, but the plants returned each year in large numbers making grazing land unusable (Kok 1975). Musk thistle infestations increased, reducing grazing acres, but herbicide control was decreasingly effective.

Since the thistle is an introduced species and none of its natural predators arrived with it, a search was made in Europe to find natural enemies that keep those populations in check. Researchers from Virginia Polytechnic Institute and State University went to Rome, Italy in the 1960's and studied a number of local phytophagous insects that are natural enemies of musk thistle (Boldt and Campobasso 1981; Kok 1975; Zwölfer and Harris 1984). *Rhinocyllus conicus* Froelich, the Musk thistle head weevil, and *Trichosirocalus horridus* (Panzer), the rosette weevil, were determined to be the safest potential natural enemies. Their life cycles coincided with the thistle and they did not appear at that time to be attracted to other thistle varieties (Boldt and Campobasso 1981; Sieburth, et al. 1983; Zwölfer and Harris 1984).

In 1969, head and rosette weevils were introduced into the United States (U.S.). During the intervening years, studies of thistle and weevil interactions have continued. Specifically, extensive work has been done in Virginia, California, and Missouri (Puttler, et al. 1978; Surles, et al. 1974; Turner, et al. 1987). Several other states have conducted weevil releases (Hilbert and Brooks, 2000; McDonald, et al. 1994).

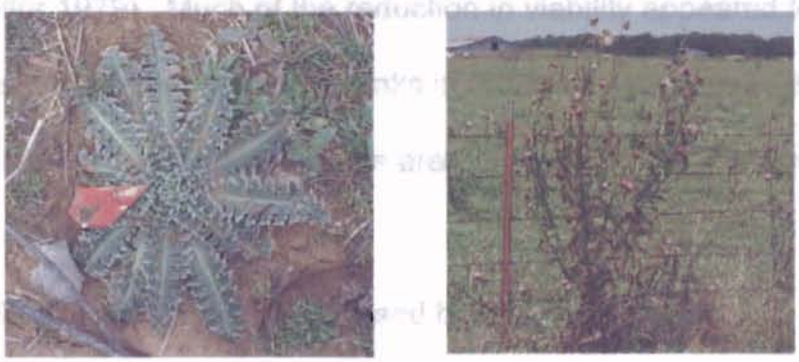
While there is evidence that the thistle head weevil has established in Oklahoma, at present no one has returned to previous release areas to accurately determine how effective these populations of head and rosette weevil have been in controlling musk thistle. To examine the effectiveness of previous release programs, studies were conducted to quantify musk thistle infestations and the effect of biological control methods in managing this noxious weed.

Musk thistle Biology

Musk thistle, *Carduus nutans*, belongs to the Order Asterales and Family

Asteraceae (Compositae). It is considered by some specialists to be a complex of species that include *C. nutans*, *C. macrocephalus* Desf., and *C. thoermeri* Weinm. (Tipping 1991). It is also closely associated and often confused with *C. acanthoides*, the plumeless thistle (McCarty et al. 1969). Height of musk thistle varies from 0.5-2.0 m, and it possesses many spiny branches and the ability to produce up to 100 heads (Desrochers, et al. 1988).

Musk thistle is a biennial, germinating in the spring, growing as a rosette the first season, overwintering, and producing blooms the second season (Fig.1.1). In many southern states it also functions as a winter annual, germinating during late summer or fall and overwintering as a rosette and producing blooms the following spring.



a) rosette b) mature plant

Fig.1.1 Musk thistle growth stages a) year one, rosette stage b) year two, bolted mature plant

Thistles produce large numbers of seeds called achenes. An average terminal head produces greater than 1,000 seeds (Beck et. al 1990). Estimates of total seed load in undamaged plants vary from 5,500 (Cartwright and Kok 1985) to > 25,000 (Jackman 1999) with germination rates of 30% (Wentworth 2000) to 90 % (Anonymous, 2001) (Roberts and Chancellor 1979).

Seed germination is affected by depth of planting and the amount and quality of light the plant receives. A period of dormancy, either innate or enforced (Anderson 1996), is not generally required. Seeds germinate after maturity, as soon as weather conditions are favorable (McCarty et al. 1969; Roberts and Chancellor 1979), frequently in 14 days with adequate moisture (Lee and Hamrick 1983). Thistle seeds buried at depths from 0-6 cm showed germination and emergence rates were highest at 0.5 cm depth, dropping rapidly at greater depths. Seed is able to germinate at depths of 3 cm but seedlings are unable to emerge from the soil (McCarty et al. 1969). Seed viability varies with soil depth and amount of damage to the seed coat. Tillage and seed burial at 2-4 cm caused high mortality rates (James et al. 1998), while seed depth greater than 7.5 cm triggers enforced dormancy for up to ten years (Roberts and Chancellor 1979). Much of the reduction in viability appeared to be caused by damage to the seed, such as breaks in the seed coat surface that occur during shallow tillage, cattle trampling the area, or freeze/thaw (heaving) injuries (James et al. 1998).

Seed germination is increased by high light levels in the red spectrum (Medd and Lovett 1978a). An alternating light and dark photophase with 8 hours of fluorescent lighting and 16 hours dark, also improved germination rates (McCarty et al. 1969). These types of conditions can be found in over-grazed pastures, areas with sparse vegetation, or where shallow tillage practices are used. Germination in low light conditions does occur but is slower and produces weaker plants. Light levels affect the temperature needed in germinating seed. The seed germinates in high light levels at 15 - 20° C, but an increase to 20 -30°

C is required in low light levels (Medd and Lovett 1978b).

Bolting and seed production requires that the plant goes through a vernalization (chilling) process. This includes a complex mix of short and long daylengths and cool/cold temperatures depending on the age of the plant and the amount of plant mass. An adequate number of vernalization hours and short days reduces the number of long days required for bolting (Medd and Lovett 1978a). Forty days, with a minimum temperature at or below 10° C, is sufficient to initiate bolting. Increasing the number of cold days allows plants to initiate bolting in greater numbers and at a faster rate (Haderlie and McCarty 1979).

Plants germinating after vernalization (spring) remain a rosette during that growing season, receive chilling hours the following winter and bolt the second spring. In areas where marginal chilling hours are available, vernalization is incomplete the first winter, plants will remain as rosettes another summer and obtain a second winter of cool temperatures. Plants not receiving adequate chilling hours during a second winter will die without setting seed (Medd and Lovett 1978a).

Once the number of vernalization hours are reached and bolting occurs, flower heads develop. Blooms are solitary and range in color from pink to purple. They are attractive to many insects, especially bees, bumble bees, butterflies, moths, and various small flies and parasitic wasps (McCarty 1982; Personal observation).

At maturity, the receptacle base of the head shrinks allowing it to assume a slightly convex shape releasing seed. Seed attached to a pappus (parachute like filament used to carry seed on the wind) are released to drift on the breeze (Desrochers, et al. 1988; Smith and Kok 1984). The pappus is fragile and breaks off very easily leaving seeds without a reliable method of dispersal. When seeds are no longer attached to the pappus they fall directly to the ground and are not dispersed causing dense patches near the original plant (Smith and Kok 1984). Research conducted on seed dispersal has shown that approximately 80% of the seed fell no further than 40 meters from the plant at wind speeds of 5.62 m/s (20.2 kph). Less than 1% of the seed will disperse more than 100 meters at that same speed (Smith and Kok 1984). Birds and other animal or mechanical transport were not considered in this study.

Musk thistle seed heads contain large numbers of seed. Terminal heads have approximately 1,000-1,200 seeds. Secondary and tertiary heads have progressively fewer seeds (Rees 1991). Very small, late season heads contain as few as 25 seeds (McCarty 1982). Seed head production and total seed counts are affected by the condition of the terminal head or basic growth conditions. If the terminal head is damaged or removed for any reason, apical dominance is broken and growth of additional branches with heads is stimulated (McCarty and Hatting 1975). In areas with ideal growth conditions plants are capable of producing 300+ heads (Lacefield and Gray 1970). Thistle control measures have included chemical sprays, mowing, physical removal, land management, and biological control. Sprays, mowing and physical removal have been ineffective and costly as long term strategies. As stated previously, herbicides have been used for many years. Growth regulating (phenoxy) herbicides 2,4-D ester, clopyralid, dicamba, picloram, and MCPA are the main types used. All of these chemicals have spray drift considerations that restrict their use to areas away from sensitive crops (Anderson 1996).

Cost of chemical control is an important consideration for landowners. The owner of Kelly Ranch, Craig Co., OK stated that he spent $5,000/yr. in chemical control on his 15,000 acre ranch until he simply gave up. A Delaware Co., Ok landowner explained his frustration at spending $3,000+/yr. in chemical control while his neighbor "upwind" does nothing (Personal Communications). By 1989, Herbicide cost to control musk thistle in Missouri was estimated at $750,000 to $1,000,000 dollars annually (McDonald et al. 1989). With increased herbicide costs, growers earn smaller net yields on pasture or hay fields.

Proper spray times are crucial to chemically controlling musk thistle. Optimal spray time occurs when the plant is still in the actively growing rosette stage (Stritzke, et al. 1999; Oklahoma Cooperative Extension Service, 1999) (McCarty and Hatting 1975). Once the plant has started bolting, chemical dosage needs to be increased (Dow Agrosciences 2001). Chemical use after bolting does not guarantee a reduction of seed set. A small number of viable seed was recorded in herbicide tests done during bolting (McCarty and Hatting 1975). Researchers in New Zealand have recorded phenoxy resistance in musk thistle during the 1980's. Their research showed a need to mix herbicides to achieve adequate control (Rahman, et al. 1994).

Mowing and physical removal are only viable options in selected situations. Physical removal involves digging rosettes while they are still small or cultivation of crop fields. Preparing fields for spring crops removes any newly germinated or overwintering rosettes (McDonald et al. 1989). Hand digging is labor intensive and feasible only if a few plants are involved.

Mowing conducted when bolting has just started must be repeated 2-3 times to prevent plant regrowth and bloom (Fig 1.2). Plants mowed after initiation of bloom allows a percentage of seeds to mature. There are enough nutrients remaining in plant tissues to support maturation of the oldest seeds (McCarty and Hatting 1975). Mowing and baling these plants as part of general forage management is a primary method of thistle spread (Stritzke, et al. 1999). Additionally, repeat mowing is expensive for growers and road maintenance workers. Many areas have topographies that are inappropriate for mowing or the land quality is too poor to support the cost of control.

Fig.1.2 Musk thistle, mowed with lateral regrowth and blooms

Established tall fescue grass pastures are able to compete well with musk thistle. A one year old fescue pasture has sufficient shading to prevent thistle seed, which requires light, from germinating. Thistles which do germinate are unable to compete for nutrients, moisture, and sunlight and a majority do not complete their life cycle (Kok, et al. 1986). Maintaining dense pasture cover and preventing cattle from over-grazing provides significant declines in thistle densities (Wardle et al. 1992).

Biological control (biocontrol) is using a living organism to control another living organism. Biocontrol's main goal is to lower pest populations below the Economic Injury Level (EIL) and maintain them at those levels. Pest populations below the EIL do not require additional control measures and reduce a growers costs. As a means of augmenting the previous control methods, natural enemies of musk thistle were obtained from Europe and have been released throughout the United States (Boldt and Campobasso 1981; Kok, et al. 1975). *Rhinocyllus conicus*, the musk thistle head weevil, and *Trichosirocalus horridus*, the rosette weevil, will be discussed individually in the following sections.

***Rhinocyllus conicus*, The Head Weevil**

The musk thistle head weevil, *Rhinocyllus conicus*, is a weevil in the family Curculionidae. *R. conicus* is a natural enemy of musk thistle, native to central and southern Europe, northern Africa and western Asia (Zwölfer and Harris 1984). Head weevils were imported in the late 1960's in an effort to control musk thistle without chemicals (Boldt and Campobasso 1981).

The life cycle of the head weevil is univoltine with larvae as the damaging life stage. *R. conicus* overwinters as an adult emerging from hibernation in mid-spring . Females oviposit eggs on the undersides of bracts on flower heads, beginning as soon as buds develop (Rees 1991). Eggs hatch within 6-8 days and larvae burrow into developing receptacle tissue, eating newly developed seeds or supporting vascular tissue. Larvae feed for approximately 25-30 days then form pupation chambers inside dead receptacle tissue. Pupation takes 8-14 days (McDonald et al. 1989) with emerging adults feeding for a short time prior to passing the summer heat underground in aestivation, followed by hibernation during the winter, emerging the following spring (Stritzke, et al. 1999).

Larval feeding by head weevils in head receptacles cuts off vascular circulation providing nutrients to developing seeds. *C. nutans* responds by producing callus material in the feeding area. This callus further occludes vascular function providing additional food for larvae to consume (Shorthouse and Lalonde 1984). Infested seed heads become distorted and filled with necrotic tissue and frass (Fig 1.3).

a) cut head, receptacle filled frass and callous tissue

b) damaged head with no seeds

c) damaged head with multiple weevil exit points

Fig.1.3 Infested musk thistle seed heads

Seeds that do develop become trapped in the seed head. Infested heads contain a sticky substance that hinders seed release. The distorted receptacle base is unable to contract and release seeds leaving them packed closely together. This inability to release seed leads to intraspecific competition when heads fall to the plant base. High rates of intraspecific competition lead to seedling death and a reduction in mature plants (Smith and Kok 1984).

When available buds have been utilized, females will oviposit on peduncle and stem areas below heads. Larvae that feed inside stem and peduncle tissue destroy additional vascular connections to the head. Thistle heads with stem and peduncle feeding frequently dry out early, causing the death of all seeds and any larvae present (McDonald et al. 1989). Low levels of weevil infestation (1-2 larvae) impact seed production (Surles and Kok 1978). Increasing numbers of larvae/head reduces the number of mature seeds. Four to five larvae/head leads to a 55% reduction in mature seed. An increase to nine larvae/head can reduce mature seed by 98% (Rees 1991).

Head weevil feeding has greater implications than just reduction of seed. Extensive studies were conducted in Virginia to determine the effect of weevil feeding on thistle seed viability (Surles and Kok 1978). They found that seed vigor and viability is time dependent. The first heads to bloom are the most vigorous, produce the most seed, and also have the highest viability levels. Secondary heads produced fewer and less viable seeds. Less viable seed produces progressively smaller and less vigorous plants. Several years of head weevil infestation reduced the overall health and vigor of thistle stands. As plant vigor declined, the impact of weevil feeding increased. They concluded that when weevils destroyed the earliest and most viable seeds, plant health decreased with only less desirable seeds available for reproduction (Surles and Kok 1978).

Areas well infested with head weevils will have high egg densities on heads. An excess of 200 eggs/head on terminal heads have been recorded. The resulting lack of oviposition sites causes females to move to new areas looking for new oviposition sites after approximately three weeks. Moving to outlying areas provides a gradation of infestation and allows a longer oviposition time frame (Rees 1991). Emigration of head weevil females varies by area. In Missouri head weevils have been recorded moving a minimum of 2.53 km per year (McDonald et al. 1989). Virginia researchers noted movement averaging 5.31 km per year, dispersing in the general direction of prevailing winds (Kok and Surles 1975).

Where head weevils have been present for at least ten years significant reduction of musk thistle in many areas is reported. Missouri and Virginia have recorded excellent long term suppression of musk thistle stands (Kok and Surles 1975; McDonald et al. 1989). Musk thistle and *R. conicus* are well synchronized, making head weevils an excellent agent for biological control (Surles and Kok 1977)

Although head weevils are a good choice for biological control there are pros and cons involved in their use. The pros include the following:

1. Cost for control is inexpensive. Once weevils have been moved into

an area they can be moved from site to site with minimal expense. Weevils also emigrate to new areas providing additional control with little effort.

2. Weevil larvae do not leave the head head they infest, so do not migrate away removing control partway through the season (Rees, 1991).
3. Larvae are rarely affected by use of herbicides in the area so control of other weeds is not jeopardized (McCarty and Hatting 1975)
4. Herbicides with their accompanying costs and hazards are not needed if an area is dedicated to using weevils alone as a control measure.
5. Weevils provide control in areas inaccessible to mowing and spraying equipment. Draws, gullies, watersheds, and rocky terrain can experience reliable thistle control even with limited access.

Cons include the following points:

1. Improper management, i.e. mowing too early in the season can destroy weevil larvae through dessication and stimulate production of secondary stems which will have no weevil infestation (McCarty and Hatting 1975).
2. Long time frames involved in control leaves producers and landowners frustrated looking for quicker management options (Personal conversations). Many landowners are looking for quick fixes. The commitment of several years seems unreasonable or unworkable to their situation.

3. Damage to other thistles has been documented. In Nebraska and Michigan, head weevils have been found in endangered native thistles (Louda et al. 1997). The full extent of this damage has not been fully assessed. Researchers in the affected areas are calling for an end to head weevil introductions as a precautionary measure (Cutler 1990; Mlot 1997).

***Trichosirocalus horridus*, the Rosette Weevil**

T. horridus, formerly *Ceuthorhynchidius horridus* (Panzer), was imported from Rome, Italy in 1970 and released in 1974 to supplement thistle control by *R. conicus* (Kok and Trumble 1979). Instead of feeding on flowers and seeds, these larvae tunnel into the thistle rosette eating basal tissue (Cartwright and Kok 1985; Trumble and Kok 1979). Although plants are not killed, many suffer sub-lethal damage reducing seed loads and ultimately decreasing thistle populations (Kok 1986).

Females oviposit up to 2,000 eggs/year into a longitudinal groove prepared in the midrib of a leaf during fall and early spring (Boldt and Campobasso 1981). *T. horridus* overwinters in the egg, larval or adult stages. Larvae hatch in 5-30 days depending on soil temperature. Warmer soils increase egg hatch rates. Length of time spent as a larva is related to season, with larvae hatching in the fall overwintering, and those hatching in early spring pupating within 6-7 weeks. Larvae leave the plant and pupate in silken chambers underground, emerging in late spring, feeding for a short time, then aestivating through the summer (Stoyer and Kok 1986) (Kok, et al. 1975).

After hatch larvae tunnel through vascular tissue in the leaves to reach the crown of the rosette, where their feeding causes tissue necrosis and death of the apical bud (Fig.1.4).

a) necrotic tissue in rosette center b) cut view c) distorted meristematic tissue

Fig.1.4 rosette weevil damage

Removing apical dominance causes the plant to grow lateral branches and become "bushy". Although branching occurs and more heads are produced, nutrients that should be producing seed are redirected to plant recovery and seed counts are lower than in uninfested plants (Cartwright and Kok 1985) (Sieburth, et al. 1983).

T. horridus is able to exert a great amount of stress on the musk thistle plant. Heavily infested plants are greatly reduced in height (Kok 1986) and seed count, particularly in smaller plants (Cartwright and Kok 1985). Plants under stress of any form are more susceptible to larval damage. The use of low-dose 2,4-D in Virginia damaged, but did not kill, thistle plants. These plants succumbed to larval damage faster than untreated plants. Herbicide use has little effect on rosette weevil larvae or female oviposition rates (Stoyer and Kok 1989).

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During the early stages of infestation, larval damage is difficult to see. Thistle plants appear to be able to resist attack, killing some of the larvae. By the third year, weevil numbers increase greatly, allowing necrotic damage to be seen. Each year plants are smaller and more stressed, producing fewer seeds which are more susceptible to larval damage. As fewer thistle plants are present each year, desired pasture or field plants have a chance to recover and compete with musk thistle (Sieburth, et al. 1983). Major reductions in thistle populations can be seen within three years, with 90+% plant reduction in 5-6 years (Kok 1986).

Rosette weevils also have pros and cons to their use. The pros are:

1. Weevils are inexpensive, once they are established it is easy to collect them and transfer them to new locations.
2. The larvae remain in the same plant their entire immature stage.
3. Weevils are unaffected by low level herbicide use and herbicide stressed plants are more rapidly damaged.
4. When used alone, rosette weevils often provide control in 5-6 years.
5. Rosette weevil larvae feed only on musk thistle rosettes, reducing the risk of damaging other plants (Rizza and Spencer 1981; Sieburth and Kok 1982).

Cons are as follows:

1. Control is not immediate. Growers and landowners may become impatient looking for a quick cure to their thistle problems.
2. Misunderstanding by producers and landowners. They may view it as "a weevil, is a weevil, is a weevil" and it must therefore be a pest.

Producer education is very important to the success of biocontrol.

3. Plants are not killed and some continue to produce low levels of seed.

Biological control using both head and rosette weevils in the same infestation has been a success. These species feed in different niches on the same plant, heads for *R. conicus* and rosettes for *T. horridus,* thereby preventing interspecific competition (Rees 1991; Sieburth, et al. 1983). The combination of infestation by both these insects has been shown to reduce the count of viable seed and reduce stands in pastures faster than using a single weevil species (Cartwright and Kok 1985). As the two weevils drain vitality from thistles and reduce plant numbers pasture growth recovers at a greater rate, which in turn reduces thistle plant vigor (Kok, et al. 1986).

Musk thistle is a serious problem in the United States. It is able to spread rapidly, adapting quickly to new areas. Control has often been ineffective and costly. By combining various control methods (herbicides, mowing, pasture and range management, and weevils) it is possible to reduce musk thistle stands by 90%. Reducing thistle stands provides more and better range for cattle, fewer losses in field crops, and eliminates some herbicide costs. All of these benefits will increase net profits and are worthy goals for all landowners and farmers.

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Chapter II

Establishment and Impact of the Musk Thistle Head Weevil, *Rhinocyllus conicus*, and the Rosette Weevil, *Trichosirocalus horridus*, for Control of Musk Thistle, *Carduus nutans*, in Oklahoma

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Abstract *Rhinocyllus conicus* Froelich, the musk thistle head weevil, was released in northeastern Oklahoma beginning in 1991 for biological control of *Carduus nutans* L., the musk thistle, with weevils released in 34 counties by 2001. *Trichosirocalus horridus* (Panzer), the rosette weevil, was released in six counties in 1998, and releases in 2000 and 2001 brought the total 29 counties. Release areas were surveyed in 2000 and 2001 to determine the level of weevil establishment . Head weevils were recovered from 30 of 34 counties. Thistle infestations were considered well infested if 30% of heads had ≥4 larvae/pupae present. Sixty-three percent of the counties had ≥25% of the sites well infested. Thistle density has been reduced in 13 weevil release counties. Rosette weevils were recovered in three of the six original release counties, and one county with no releases up to that date. A combination of head and rosette weevils present in the rosette weevil recovery areas provided a synergistic reaction with thistle density reductions occurring faster than in head weevil alone sites. Head weevils have established in Oklahoma and are reducing thistle infestations. Rosette weevils are established in several of the1998 release areas.

Key Words *Carduus nutans*, *Trichosirocalus horridus*, *Rhinocyllus conicus*, musk thistle, head weevil, rosette weevil

Carduus nutans L., the musk thistle, has been present in Oklahoma since the middle 1940's. By 1960,It spread through much of northeast Oklahoma (Stritzke et al. 1999). Chemical, cultural, and mechanical control methods have been used with unsatisfactory results. In 1994, an increasing problem prompted Oklahoma's Legislature to enact House Bill 1048 declaring musk thistle a noxious weed in Craig, Delaware, Ottawa, and Mayes counties. HB1952, the most recent revision, includes all counties and provides rules allowing county commissioners, Department of Transportation, or any other official entity to provide enforced control and bill the landowner (Oklahoma Noxious Weed Laws and Rules, 2000).

Other control measures having been ineffective, biological control was attempted in 1991 using *Rhinocyllus conicus* Froelich, the musk thistle head weevil. Weevil larvae infest musk thistle seed heads, consuming developing seeds and receptacle tissue. Adult weevils were collected from Missouri and released in twelve northeastern counties. Head weevils were collected for distribution from Missouri until thistle populations there were reduced to low levels making it non-feasible. Several counties in Oklahoma had large enough head weevil populations within five years to begin redistribution from these counties to other areas of the state. All weevils distributed in Oklahoma now come from infestations in northeast and central areas of the state.

Head weevils take up to ten years to effectively reduce thistle stands (Kok and Pienkowski 1984; Kok and Surles 1975). To speed up thistle reduction, an additional biological control agent, *Trichosirocalus horridus* (Panzer), the rosette weevil, was introduced into six counties in 1998. Insects for the initial collection were obtained from the Manhattan, Kansas area. Extension personnel from Oklahoma returned to the same area in 2000 to collect additional weevils. Rosette weevils were also recovered and redistributed from Rogers Co. in both 2000 and 2001.

Since the beginning of weevil releases in Oklahoma, no evaluation of their effectiveness in controlling musk thistle has been conducted. The purpose of this study was to visually survey as many release sites and their surrounding areas as could be identified, talk with landowners about thistle reduction, and assess weevil spread. Survey results will be used to determine weevil establishment and evaluate their effectiveness controlling musk thistle.

Materials and Methods

During the summers of 2000 & 2001 thirty-six counties where head weevil releases had occurred between 1991 and 1999 or bordered release counties were surveyed. Surveys followed several steps. Records from previous head weevil releases were checked and county Extension Educators were contacted for updated release lists. Landowners who had made releases were contacted via mail to obtain permission to check thistle infestations on their land. Approximately 50% of the landowners responded.

Extension Educators in counties with head weevil releases were contacted by mail to request current information on thistle infestations. Follow-up phone calls were done when needed. In areas where Extension Educators were unable to supply information, county road crews and Department of

Agriculture employees were contacted for thistle information. Over the course of ten years some records of head weevil releases were lost due to Extension Educator transfers and landowners moving or dying. Locations were also lost when recipients of head weevils released them in different areas than they originally planned or gave them away without notifying their local county Educator.

Musk thistle. Infestations of musk thistle were recorded by location using the official Oklahoma road numbering system. Levels of thistle infestation were compared to the levels in Oklahoma's Noxious Weed Law Rules. Light infestation: less than two plants/acre (5/ha); medium: two-nine plants/acre (5-24/ha);and heavy: ten or more plants/acre (25+/ha) (Oklahoma Noxious Weed Law Rules, 2000).

Head weevils. As many release sites as possible were visited. At each location fifty thistle heads were removed randomly throughout the patch, bagged, dated, and location noted. Unusual characteristics at each site were recorded. After visiting known release sites, the surrounding area was checked for several miles in all directions for additional thistle infestations. Thistle heads were collected from these areas to check weevil spread. Where no information was available on weevil releases, or counties bordered on release areas, roads were traveled in a grid pattern to cover as much territory as possible. Thistle patches were identified and heads bagged as stated earlier.

Landowners and growers were visited when available, questioning their experiences with head weevils and how they assessed effective thistle control.

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Land management practices were discussed to assess their effect on thistle control. Musk thistle educational material from OSU Extension was provided to growers at every site visited.

In 2000, counties in northeastern Oklahoma were surveyed. Digital photos were taken and detailed maps made to verify thistle infestations. Large thistle infestations with head weevils were rechecked in 2001. After these counties were rechecked, counties in central and west central Oklahoma were surveyed.

Heads from both years were brought to the lab and frozen until they were processed. Each head was measured in mm at the receptacle base and number of larvae, pupa, or pupal cases counted. Heads collected in 2001 had the percent of visible damage estimated. Any insects doing damage to seed production were recorded.

Rosette weevils. In 2000, counties with rosette weevil releases were surveyed using the same procedure as for head weevils. In early spring, before thistle plants bolted, roots were dug and brought back to the laboratory for larval counts. Any rosette weevil adults captured outside of release areas were preserved as voucher specimens.

Results

General observations. Landowner and grower satisfaction with head weevils for thistle control was related to their initial expectations. Growers who were unable physically or financially to use herbicides were willing to allow time for weevils to reduce thistle stands. Undisturbed, weevils began reducing thistle

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stands in as little as five years. Several growers provided reports of what they viewed as significant reductions in three years (Personal Communications). Growers who were impatient and mowed thistles out of phase with plant and weevil growth or applied herbicides after bolting had slower reductions in their thistle stands.

Weevils spread into surrounding areas, generally following the prevailing winds. Counties with only one or two known release sites had weevils scattered throughout the county. Payne Co. is an example of this, with only two releases done in the early 1970's, and weevils now established throughout the county.

Thistle infestations were conspicuously absent in areas with native grasses and prairie plants or heavy shade. Most infestations occurred in ditches, pastures with weak stands of grass, disturbed or abandoned areas, and winter wheat fields. Draws and gullies that facilitated seed movement had especially heavy thistle infestations.

Musk thistle density. Fig. 2.1 shows surveyed thistle infestations in Oklahama, beginning in 1990, with areas musk thistle has spread into by 2001. These sites have been verified in 1990 by Extension Specialist Bill Stacy, an Extension Service survey in 2000, and during this study by actual visitation or by speaking to Extension Educators from involved counties.

Figuring thistle density per site was not a feasible exercise in most locations. Pasture sizes of 16.2-64.7 ha (40-160 acres) were too large and patches of thistle in them too varied to conduct density counts in a timely manner. It was decided to consider any area with a thistle infestation over 1 ha

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(2.5 acres) as a large site and make visual estimates of thistle density. In a majority of sites density was heavier than the numbers established for heavy infestation by Oklahoma's Noxious Weed Law Rules. Using densities measured in growth studies during 2000-2001 (Roduner 2001), some sites had thistle densities approaching 20,000 plants/acre (50,000/ha). Notations were made of areas with extremely heavy plant densities.

Reductions in thistle size and vitality, with head weevil infestation and dense pastures were observed in studies done in Virginia. Weevils consumed the most viable seed, leaving less viable seed to enter the soil seed bank and as the vitality of thistles decreased, pastures were able to recuperate, competing with the thistle for space and nutrients. This effect appeared synergistic with an ultimate 'crash' in the thistle population earlier than weevils alone would have achieved (Kok et al. 1986; Kok and Pienkowski 1984). Locations in Oklahoma where weevils have been in place for six to ten years showed this type of reaction to weevils. Sites with heavy infestations of weak thistle plants in 2000 did not exist in 2001. In several counties the results were very dramatic. Fig. 2.2 shows all counties with reductions in thistle density either viewed from differences between 2000 and 2001, or reports from Extension Educators. Three counties had rosette weevils recovered, with an additional reduction in thistle vitality.

Head weevil density. Since 1991, head weevil releases have been conducted in Oklahoma. Fig. 2.3a depicts the location of weevil releases by counties. Large numbers of weevils per head are not needed to significantly

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reduce seed production. One or two larvae per head causes some seed reduction (Surles and Kok 1978), four to five larvae/head leads to a 55% reduction in mature seed, and an increase to nine larvae/head can reduce mature seed by 98% (Rees 1991).

Thistle heads from each county were processed and all heads with four or more larvae and/or pupae per head were considered well-infested. The percentage of well infested heads in each sample of fifty heads was calculated. Thirty percent of heads at a site containing four or more larvae and/or pupae meant the site was well infested. The number of well infested sites per county were divided by the total number of sites sampled, resulting in the percentage of well infested sites in each county. These numbers were used to determine weevil establishment in each county. Fig. 2.3b provides a summary of weevil infestation levels by counties. Exact percentages will be reported with each county. Weevils were considered recovered from a site if larvae, pupae, or empty pupal chambers were found inside thistle heads.

Large numbers of head weevil larvae were supported by thistle heads. When 15-25 larvae or pupae were present in a single head, it frequently appeared dry, shriveled and brown as if burned by a blowtorch (Fig 2.4). Head weevil infested thistle heads from 2001 had the percent of physical damage and number of larvae, pupae, or pupal chambers recorded. The relationship of damage to number of pupa and head diameter was investigated (4,962 infested thistle heads) with Sigma Plot (SPSS Inc. 1986-1987) and a 3-D graph (Fig. 2.5) was created. The percent of damage increased rapidly when weevil levels were

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greater than six. Fifteen or more weevils caused 100% damage in heads 20 mm and larger.

Head weevil survey by county. To provide the most accurate information, counties surveyed will be dealt with individually.

Adair Co. First recorded weevil releases were in 1992 with subsequent releases the following years. Musk thistle infestations are mainly in the northern half of the county, with the heaviest along CR E660 (Chewey Rd.) between U.S. 59 & SR 10 and CR D63 north of Chewey. In 2000, infestations were very heavy with areas containing estimates of several thousand plants per acre. Fifty percent of the collected samples were well infested. On revisiting these sites in 2001, all locations but one had up to 50% reduction in thistle density. Rosette weevil adults were recovered from two locations near Chewey and will be discussed in the rosette weevil subsection.

Alfalfa Co. The first recorded weevil releases were in 1999, and the survey was conducted in 2001. Heavy thistle infestations are present across the southern half of the county, with 40% of the sites well infested with head weevils.

Blaine Co. There has been no recorded release of head weevils. Thistle infestations are mainly confined to the extreme northeastern end of the county. The county was surveyed in 2001 with no weevils recovered.

Caddo Co. The first recorded weevil releases were in 1997, and

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the area surveyed in 2001. Most thistle infestations are in the northeast section of the county with several heavily infested areas near Anadarko. None of the areas had well infested heads, but 60% had low levels of weevils.

CANADIAN CO. There have been no recorded releases of head weevils in the county. The county was surveyed in 2001. Thistle infestations are mostly small and scattered, with a large heavy infestation at U.S. 270 & CR N2690. Only one site had two weevil infested heads. Thistle infestations in this county are nearing an explosion point and need rapid intervention.

CHEROKEE CO. Head weevils were first released in 1991, with additional releases in following years. The county was surveyed in 2000. Massive thistle infestations were located in the far northeast corner of the county bordering with Adair county and the Chewey area (Black Fox Hollow). A large number of heavy infestations occurred in the west and northwest areas of the county. Thistle plants were tall but thin and had six or fewer heads. All sites had head weevils present with 36% of sites considered well infested. In 2001 the most heavily infested areas were revisited, and 50% of the sites had reductions in thistle density of 70-90%.

CLEVELAND CO. No head weevil releases have been recorded. Very little thistle is present, with several small areas in the northwest corner of the county. No weevils were recovered.

CRAIG CO. Head weevils were first released in 1991, with frequent

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releases in subsequent years. The county was surveyed in 2000. Several areas in the county's western quarter, particularly along U.S. Hwy 60 had massive thistle infestations. The Peabody Coal Mine (abandoned) had three square miles (7.8 km$^{2)}$, with a density of one plant/0.8 m^2 - 1.3 m^2. Plants were tall, thin and had only three or four heads each. The Kelly Ranch near White Oak is reported to have had massive thistle infestations in the past but has achieved excellent control using only head weevils. 71% of sites visited were well infested with head weevils. The area was revisited in 2001. The Kelly Ranch, Peabody Coal Mine and surrounding areas had thistle reductions over 90%. See Fig. 2.6 for comparison photos of the Peabody Coal Mine thistle in 2000 & the reduction in 2001.

CREEK CO. Head weevil releases are recorded in 1999, but no records were kept so these sites were not visited. Three locations in the county with thistle were checked in 2000, and no weevils were recovered. Thistle density in this county is very light.

DELAWARE CO. Initial head weevil releases occurred in 1991 with over 100 estimated releases during the following years. The county was surveyed in 2000. Musk thistle is in large infestations throughout the central and southern regions of the county. Plants are tall and thin, and in several areas shorter than normal. Sixty-three percent of sites visited were well infested. The county was revisited in 2001 and half of the sites visited in 2000 had thistle density reductions of 50-90%. Three of these

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areas had no other form of thistle control. Thistle infestations at the Zena Holiness Church, 3 miles east of Zena, and a pasture 1.5 miles east of the church had adult rosette weevils. Their presence will be discussed under the subsection devoted to rosette weevil.

GARFIELD CO. The first recorded head weevil releases were in 1999 and the county surveyed in 2001. Very heavy infestations, some encompassing 50-100 acres (20.2-40.5ha), are scattered throughout the county. Head weevils were recovered from all but one of fifteen sites and 40% of the sites were well infested. The county is positioned for good control of thistle in four to five years.

GRADY CO. The first recorded weevil releases were in 1999 and the survey was done in 2001. Very heavy infestations are located in the central and northeast areas of the county. 44% of sites had weevils recovered and 22% had well infested heads.

GRANT CO. The first recorded weevil releases were in 1999 and the county surveyed in 2001. Heavy to massive infestations, some as large as 100 acres (40.5 ha) were scattered over the county. Infestations in winter wheat fields were reported, but field preparation for a new wheat crop, plowed thistles under. Weevils were recovered from all sites surveyed with 50% well infested. The county is positioned for good control of thistle within five years.

KAY CO. Initial weevil releases were done in 1995 with the county survey done in 2001. Very heavy weevil infestations were scattered

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throughout the county. Head weevils were recovered from all locations, and 64% were well infested. The county is in a good position for thistle control in three to five years.

KINGFISHER CO. There have been no recorded releases of head weevils, and the county surveyed in 2001. Small areas of thistle were located in the eastern and southern sections of the county, with only two areas containing very heavy infestations. Head weevils were recovered from five of thirteen locations. One location was well infested.

LINCOLN CO. Head weevils were released in 1993, and the county was surveyed in 2000. Only two locations contained thistle, one in the town of Carney, was well infested. The area of earlier weevil releases had a heavy thistle infestation. In 2000, no thistle was found at the site or within five miles in all directions.

LOGAN CO. There have been no recorded weevil releases in the county. The survey was done in 2001. Other than one heavily infested location, musk thistle was present in small light infestations. Head weevils were recovered from three of four collection sites and 50% were well infested.

MAJOR CO. Weevils were first released in 1999 and the county was surveyed in 2001. Massive infestations are scattered throughout the county. Weevils were recovered from every collection site, but none were well infested.

MAYES CO. Weevils were first released in 1991, and were released

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frequently in subsequent years. The county was surveyed in 2000. Heavy thistle infestations were scattered around the east and southern parts of the county. Weevils were recovered from all collection areas with 58% of the sites well infested. In 2001, a revisit over 50% of the sites showed reductions in thistle density. During conversations with three growers they all expressed satisfaction with the control achieved by weevils.

McClain Co. Weevils are recorded being released in 1999, but were not found. The county was surveyed in 2001. Thistle was found only in the area of Blanchard. No weevils were recovered.

McIntosh Co. Weevils were released once in 1992. The county was surveyed in 2001. No thistle was found on the survey, verified by the Extension Educator. No records remain of thistle levels at the time of release, but the weevils appear to have controlled it.

Muskogee Co. Weevils were released first in 1991 with subsequent releases in the next three years. The county was surveyed in 2001. No thistle was found during the survey. Extension personnel stated there was no longer a thistle problem.

Noble Co. Initial weevil releases were done in 1998. The county was surveyed in 2001. Heavy infestations were scattered through the eastern and southern areas of the county, with many thistles along U.S. Hwy 177. Weevils were recovered from all collections sites but one, and 84% were well infested. The county is well positioned for good thistle

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control in three to five years.

NOWATA CO. Weevils were released in 1991 and in subsequent years. Massive thistle infestations were located in the eastern end of the county bordering on Craig Co. and the Peabody Coal Mine. Smaller areas were scattered through the county. Weevils were recovered from all collection sites but one, and 33% were well infested. In 2001 the eastern side of the county was revisited and thistles were reduced by 95%.

OKFUSKEE CO. Weevils were released in 1991 and released frequently in subsequent years. The county was surveyed in 2000. Heavy thistle infestations were located in the northeast and central areas of the county. Weevils were recovered from all collection sites, and 75% were well infested. The area was revisited in 2001 during a head weevil round-up. Very little thistle remained in the county. The weevils are providing control of the thistle.

OKLAHOMA CO. There have been no recorded releases of head weevils in the county. The county was surveyed in 2001 with only areas outside the metropolitan areas checked. Two locations had thistle, one well infested with weevils and the other with none.

OKMULGEE CO. Weevils were first released in 1991, and the survey done in 2001. Thistle is located mainly in the northern and far western areas of the county. Infestations were small and scattered. Weevils were recovered from each collection site, but none were well infested.

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OSAGE CO. Weevils were first released in 1993. The county survey was done in 2000, and thistle is present only in the southwest corner, a loop near Ponca City. Infestations were small, ranging from moderate to heavy. Weevils were recovered from all areas and 64% of sites were well infested. The county was revisited in 2001 with 50% of sites showing reductions. Only one area had an increase in thistle, and weevils were present in the infestation. The county is positioned well for good thistle control in three to four years.

OTTAWA CO. Records about weevil releases conflict. One set of data has weevil releases listed in 1991 &1992, while another report suggests that there have been no releases. The county was surveyed in 2001 with very little thistle present. All sites were lightly infested. Weevils were present in all but one location, and 25% of the sites were well infested.

PAWNEE CO. No head weevil releases are recorded. The Extension Educator is very proactive and there is almost no thistle in the county. One location had enough plants to collect thistle heads, and a low number of weevils were present. This site is near the Payne Co. border and weevils may have migrated north.

PAYNE CO. Weevils were released at two sites in the early 1970's. No further releases were made in the county. The county was surveyed in 2000. A majority of thistle is located within fifteen miles of Stillwater. Weevils are present throughout the entire county, especially in road

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ditches. Resurvey in 2001 was difficult, due to ditch mowing.

ROGERS CO. Weevils were released in 1991 and in subsequent years. The county was surveyed in 2001. Thistle infestations are scattered throughout the county varying from very light to very heavy. Weevils were recovered from all locations and 71% of the sites were well infested. Rosette weevils released in1998 have also had an impact on certain stands. This will be dealt with in the rosette weevil subsection. The county is well positioned for good thistle control in three to four years.

SEQUOYAH CO. Weevil releases are recorded for 1992. The county was surveyed in 2001 with statements by county road crew supervisors that there is no musk thistle in the entire county. Thistle appears at this time to be under control.

TULSA CO. Weevil releases are recorded in 1991, with intermittent releases in subsequent years. In 2001 sites surrounding the greater metropolitan area were surveyed. Most infestations were moderate to heavy with several massive patches. Weevils were recovered from all but three locations. Twenty-three percent of sites were well infested with the remainder having very low weevil numbers.

WAGONER CO. Weevils were released in one location each for 1991 and 1992. The county was surveyed in 2001. Heavy infestations of thistle were present in the northwest and west central areas of the county. Weevils were recovered from around the Coweta release area up to New Tulsa, with 38% of sites well infested. No weevils were recovered or

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thistle identified from the town of Wagoner.

WASHINGTON CO. Two releases of weevils were done in 1992 and 1993 in the southern quarter of the county. Records were not kept of the release areas. The county was surveyed in 2000 with infestations varying from light to heavy. Weevils were recovered from four locations, three in the southern half of the county. None of the sites was well infested. Revisiting the area in 2001 revealed three sites with reductions in thistle density.

Rosette weevil survey by county. Larvae from *T. horridus*, the rosette weevil, tunnel into plant roots feeding on the meristematic tissue. Feeding leaves a black mass of frass and necrotic tissue in the rosette center. Apical dominance is broken, multiple short stems are produced with a reduction in heads and seed production. Fig. 2.7 shows damage to the rosette and reduced plant height compared to normal plants. Fig.2.8 summarizes all rosette weevil releases, recoveries, and areas with possible damage.

Of the seven counties where rosette weevils were released in 1998, only four release sites can be identified now. Each county will be discussed individually.

1998 releases.

CHEROKEE CO. The one landowner who released weevils did not respond to a request to check his land. The exact location of release is unknown.

CRAIG CO. Weevils were released at the Kelly Ranch in 1998 and

2000. No adult weevils have been recovered. Rosettes were dug during the spring of 2001 and no larvae were recovered. The weevils do not appear to have established.

DELAWARE CO. Two releases were done in the Jay area. In 2001, adult weevils were recovered along SR 127. The first location was 0.5 miles west of U.S. Hwy 59 in a large pasture with heavy infestation of musk thistle. Approximately 50% of plants showed evidence of rosette weevil damage. The second site was the Zena Holiness Church, 2 miles west of U.S. Hwy 59. Over 75% of plants had evidence of rosette weevil damage. This population could be controlled in two years.

MAYES CO. Weevils were released in two locations. In both areas thistle density has been reduced to levels where no weevils are present. The landowners state satisfaction with the control weevils provided.

MCINTOSH CO. Three sites at the edges of the county had weevil releases with no records kept of the release. No thistle exists in the county at this time per the Extension Educator.

PAWNEE CO. One release site with no thistle remaining. The landowner sprayed or physically removed all thistle. The Extension Educator is very proactive with thistle control, so very little thistle remains in the county.

ROGERS CO. Rosette weevils were released at one site in 1994, but the landowner did not respond to a request to survey his land. Weevils were also released on two sites at the Bell Ranch north of

Claremore. Thistle infestations had been massive over several thousand acres. During weevil collections at this site in 2000, approximately 40% of the weevils recovered were rosette weevils. In 2001, approximately 90% of weevils collected were rosette weevils. Thistle density is greatly reduced at this site. Over 75% of the plants show rosette weevil damage, with a possible population crash within two years. Roots were dug during the spring of 2001 and 45-60 larvae per root were counted. Fig. 2.9 shows the rosette weevil damaged plants at Bell Ranch.

ADAIR CO. Rosette weevils were not released in the county until June of 2000, but adult weevils were recovered in May of 2000 from a herbicide test plot two miles south of Chewey. Seventy-five percent of plants in this pasture had weevil damage. Roots were dug and checked for larvae. Biennial plants had up to fifty larvae per root and winter annuals had three to ten larvae per root. By 2001, adult weevils were recovered from a large pasture one mile north of the test plot, and 30-40% of plants had evidence of rosette weevils. Records from early head weevil releases revealed that weevils collected from Missouri occasionally had a few rosette weevil adults contaminating the samples. It is possible that the weevils in this county came from such contamination and have multiplied and spread to nearby fields controlling thistle.

Rosette weevil releases. In 2000, weevils were collected from Kansas and Rogers Co. They were released in a total of twenty-two counties. In 2001, weevils were collected in Rogers Co. and distributed to new locations in the same counties and at least three additional counties. Several counties in western Oklahoma shared their weevils with other counties but records were not kept for all releases. A total of twenty-nine counties have had rosette weevil releases to this date.

Other insects. In 2000, thistle heads from Cherokee and Delaware counties had empty dipteran pupal cases. Several sites in each county had up to five pupae/head. The pupal cases were clear, blue or black and empty making identification impossible. Only occasional diptera pupal cases were present in 2001. Larvae of *Homeosoma elactellum* (Hulst), the sunflower moth, were present in thistle heads in small numbers during 2000, with greatly increased numbers in 2001. Various locations had high levels of larvae in secondary and tertiary heads. The larvae fouled heads with their webbing and frass making seed release difficult. Smaller heads were totally consumed by the larvae.

Discussion

Head weevils have effectively reduced musk thistle densities where they have been in place for longer than six years. Since the release program has begun, thirteen counties have had reductions of thistle stands. Weevils were recovered from thirty of thirty-four release counties and twenty-five counties had sites that are well infested. Head weevils have spread from their original release sites infesting thistles in surrounding areas.

Adding rosette weevils to locations already infested with head weevils provides additional control (Cartwright and Kok 1985; Kok et al. 1986). Rosette weevil recovery areas in Adair, Delaware and Rogers counties all had head weevils present first. When the rosette weevil populations began to increase, thistle populations dropped faster than with head weevils alone, verifying the results of both Cartwright and Kok (1985) and Kok et al. (1986). Since the weevils occupy different feeding niches there is no direct competition.

Head weevil population increases are rapid (Kok and Surles 1975; Rees 1991), so sites that were considered well infested (30% of heads had >4 larvae/pupae per head) would be heavily infested within one or two years. Rosette weevils proved to increase more rapidly than head weevils, especially at the Rogers county. site. Counties with both head and rosette weevils can anticipate rapid reductions of thistle infestations.

Sunflower moth larvae, although a pest of commercial sunflower fields, did provide thistle seed reduction. Infestations of sunflower moths have been noted in other areas of the country, and their effectiveness was related to their numbers (Goyer 1978). Levels of sunflower moths vary from year to year (McCarty 1982) and they can be considered beneficial only if they do not affect nearby cash crops.

Actual musk thistle densities are much higher than those described in the Oklahoma Noxious Weed Law Rules. High density is listed as ten thistle plants per acre, or one plant per 4,356 square feet. Actual thistle density in several locations was as high as 20,000 plants per acre, or one plant per 2.2 square feet. Grower education about musk thistle growth patterns and it's ability to reproduce explosively is of paramount importance. It is easy to discount densities as low as those in the Noxious Weed Law, but the thistle must be controlled when populations are this low, preventing the heavier infestations.

The head and rosette weevil release program has been a success in northeastern and central Oklahoma. *R. conicus*, the head weevil, has become established in Oklahoma, especially where it has been in place for at least four years. Musk thistle infestations have shown reductions in density and plant vigor. The addition of *T. horridus*, rosette weevils, is speeding the reduction of thistle. Efforts must not stop at this point. Thistle populations in the western half of Oklahoma have had weevils for only one or two years and need time to establish. Continued head and rosette weevil releases and grower education to manage them will reduce thistles in the remainder of the state, allowing growers profitable use of their land.

Acknowledgments I would like to thank all the landowners and Extension personnel who provided information about thistle infestations and my lab helpers Tererai Nyamanzi, Audrey Sheridan, and Penny Potter for processing thousands of thistle heads. I also am grateful to USDA-APHIS for all the survey and weevil release work they have supported in previous years that brought us to this point.

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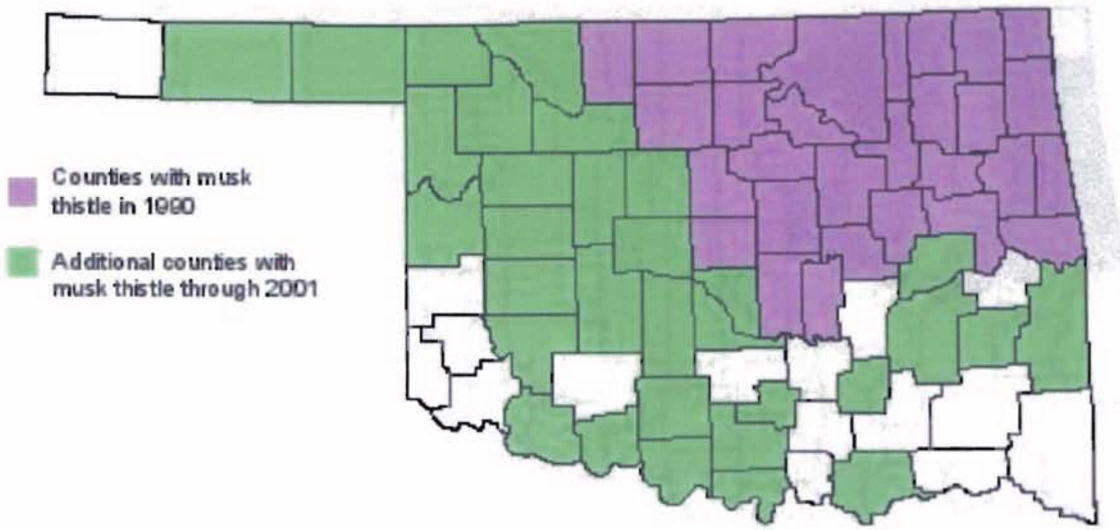


Fig. 2.1 Musk thistle locations in Oklahoma verified by survey
1990 locations verified by Oklahoma Extension Service, Bill Stacy
Additional counties with musk thistle verified by Extension Survey, 2000 and this study

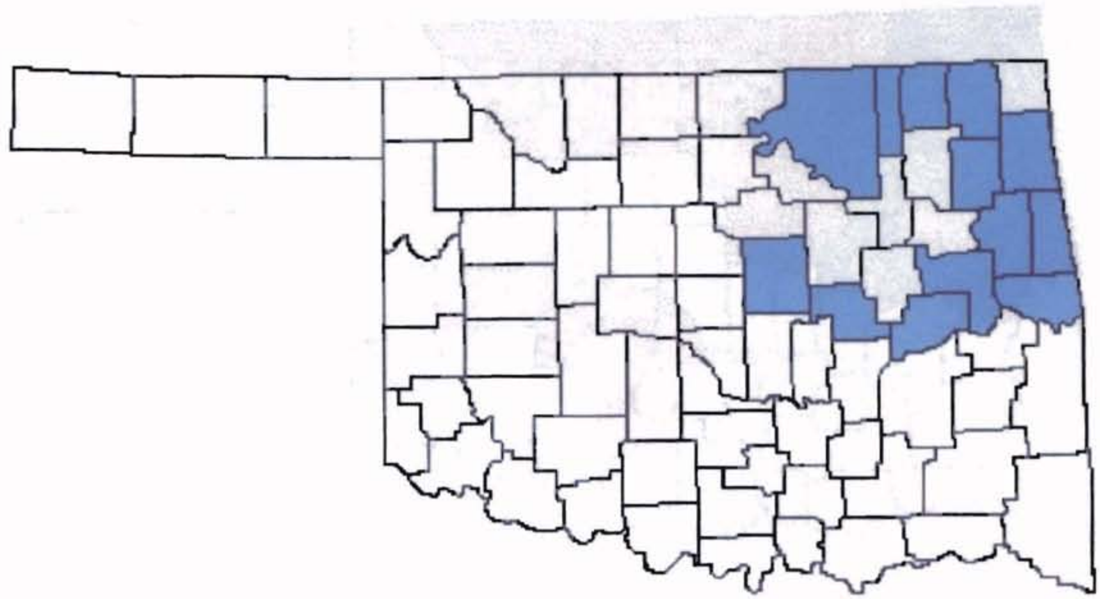
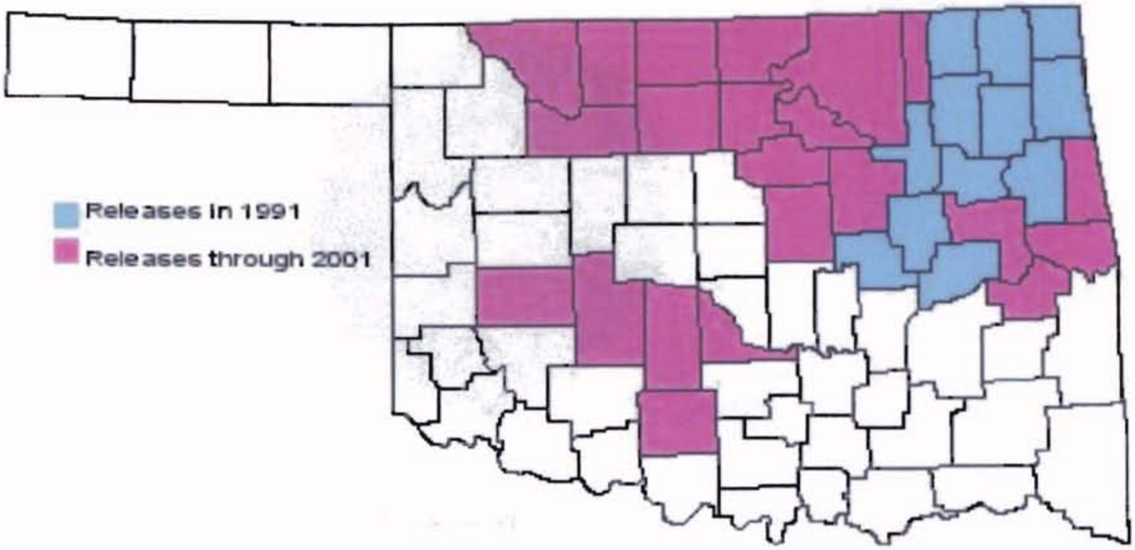
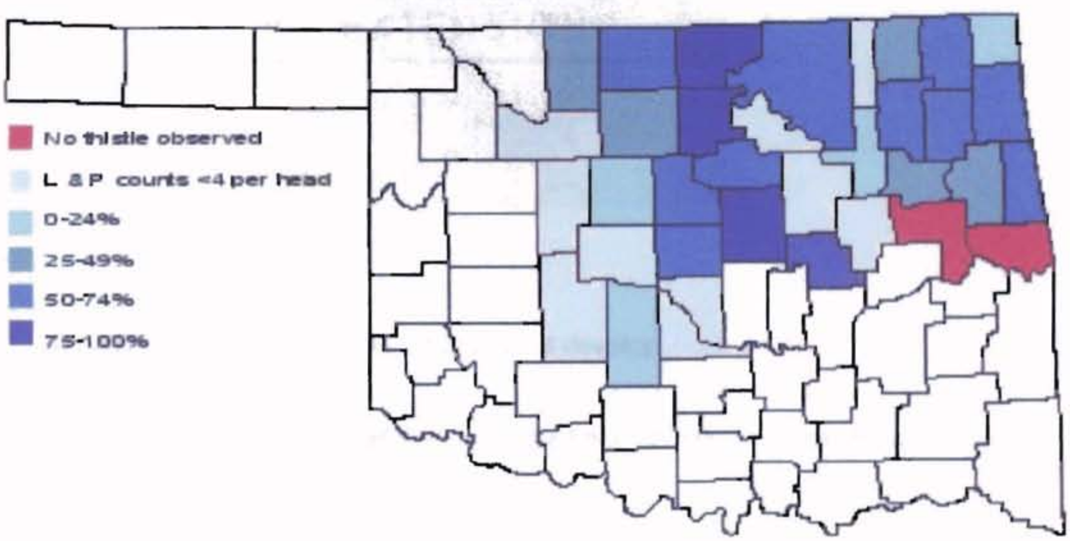


Fig. 2.2 Oklahoma counties with reductions in musk thistle density in 2001 from densities noted in 2000



a) Head weevil release sites from 1991 through 2001



b) Head weevil recovery sites in 2000 & 2001

Fig. 2.3 Head weevil release and recovery sites. a) release sites b) percentage of counties with 30% or more of the heads/site with >4 larvae or pupa (L & P) per head.

a) uninfested and all seeds released

b) heavily infested, no seeds, head did not develop

Fig. 2.4 Comparison of head weevil infested and uninfested musk thistle heads

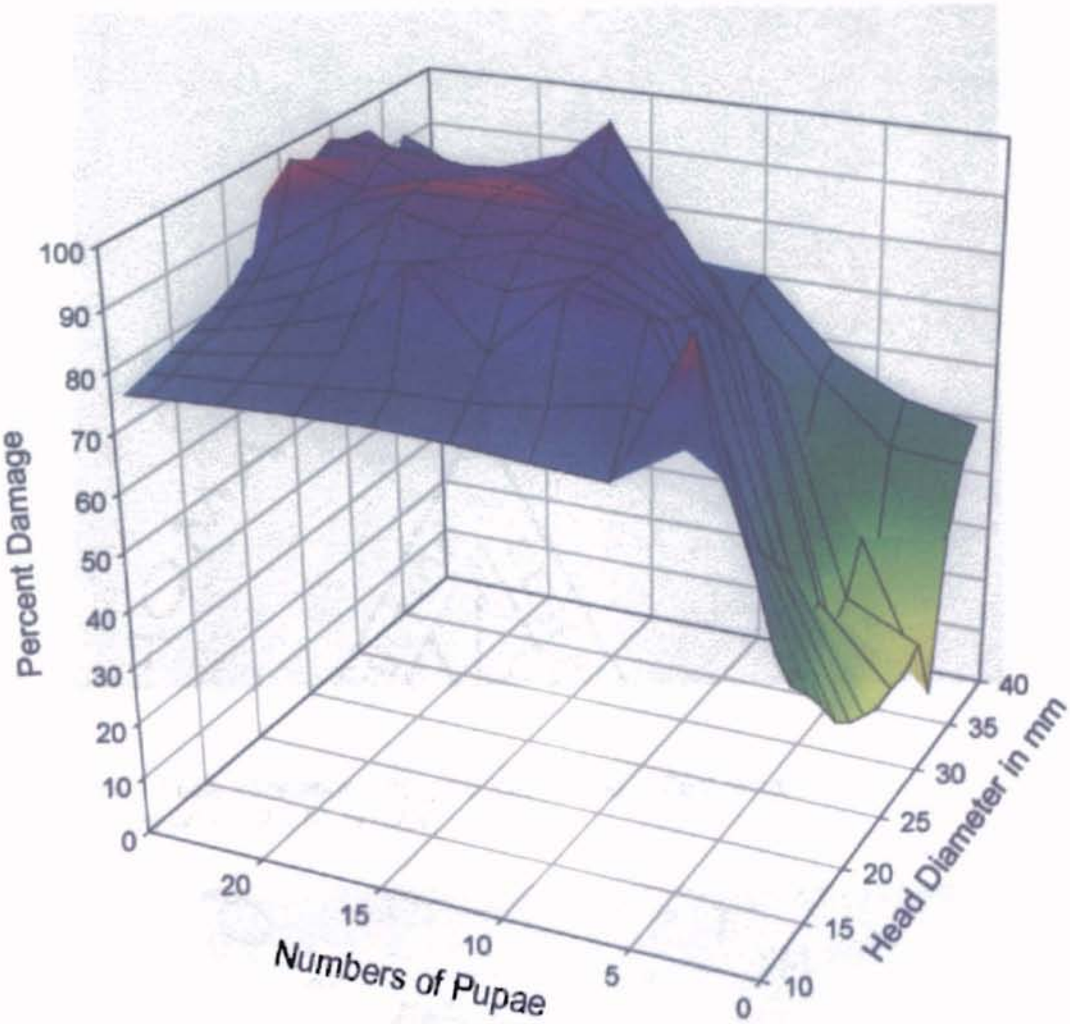


Fig. 2.5 Head weevil infested thistle heads. Physical damage increases dramatically when numbers of pupae reach six and higher in all head diameters.

a) Heavy thistle infestation, Craig Co. Old Peabody Coal Mine,
Hwy 60 & CR 210, 6/15/00

b) same site in April 2001, reduction in musk thistle

Fig. 2.6 Reduction in musk thistle population after head weevil infestation, a comparison between 2000 & 2001

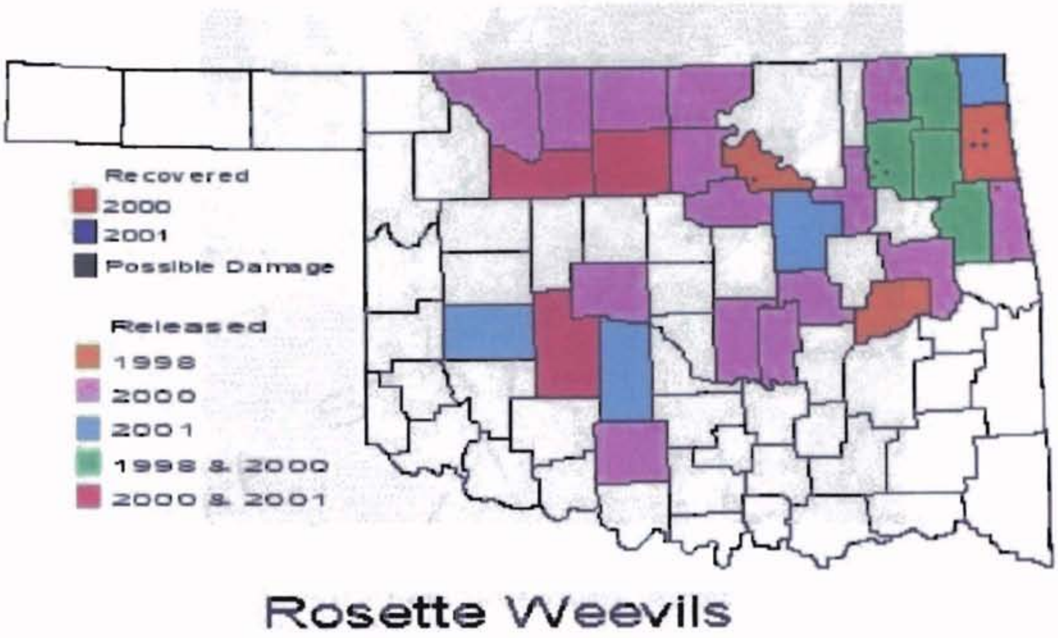


Fig. 2.8 Rosette weevil release and recovery sites from 1998-2001

a) rosette weevil damage in musk thistle rosette, necrotic tissue in center of plant, 3/20/01, Bell Ranch, Adair Co.

b) normal musk thistle, height ~ 1450 mm (plants located in Payne Co.)

c) musk thistle plants stunted by rosette weevil, ~ 550 mm, note multiple stems caused by larval damage

Fig.2.7 Rosette weevil damage, Rogers Co., Bell Ranch (photo of normal height plants provided for comparison with rosette weevil damaged plants)

Fig. 2.9 Rogers Co., Bell Ranch, rosette weevil damaged musk thistle plants, note reduction in height and multiple stems giving a bushy appearance

Chapter III

Musk Thistle, *Carduus nutans L.*, Growth in Oklahoma

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Abstract Growth data on *Carduus nutans* L., the musk thistle comes mainly from Virginia. Climate differences in Oklahoma, hotter drier summers and colder winters, made it necessary to study musk thistle growth through an entire lifecycle. Plants monitored at Lahoma and Stillwater were three weeks ahead of growth rates in Virginia. Dormancy ended in late February to early March, bolting initiated in early April with blooms in middle to late May. *Rhinocyllus conicus* Froelich, the musk thistle head weevil, is present as soon as bolting occurs and are active for 5.5 weeks, ovipositing for four weeks. Plants reached senescence in early July. Overcrowding at the Lahoma site led to less vigorous plants, high mortality rates, slower bolting, and reduced seed production. Larvae of *Homeosoma elactellum* (Hulst), the sunflower moth, were present in secondary and tertiary heads at Stillwater feeding on pollen, seeds, and receptacle tissue. Frass and webbing from the larvae fouled heads preventing seed release, providing additional thistle control.

Key Words *Carduus nutans*, *Rhinocyllus conicus*, musk thistle, head weevil

In Oklahoma, musk thistle, *Carduus nutans* L., is an exotic plant causing serious problems for landowners, managers and environmental specialists. The presence of musk thistle in Oklahoma was first recorded in Payne Co. during the 1940's, spreading throughout the state by the 1990's (Stritzke et al. 1999). It competes well with desirable plants, reducing values of fields and pastures and the crops they produce. One *Carduus* plant on 1.49 m^2 (6711 plants/ha) can reduce pasture yields by 23% (Trumble and Kok 1982) by competing for space, light, and nutrients. Musk thistle easily invades poor soils, overgrazed or thin pasture areas, roadside ditches, waste areas and crops (Medd and Lovett 1978b). Control of this weed has been a priority for many farmers, producers, and Extension Educators.

The majority of research done on musk thistle has occurred in Virginia, Missouri, Montana, Nebraska, and California. Each of these states has a climate different from Oklahoma (National Climate Survey 1988). Table 3.1 contrasts the weather differences between these states, highlighting Oklahoma's unique climate. Comparing field observations to published phenological data from Virginia seems to show a different growth pattern in Oklahoma. These patterns in Oklahoma vary enough from the published norm to justify studying plant growth. The purpose of this study was to follow both biannual and winter annual musk thistle lifecycles for a complete generation.

Materials and Methods

Areas with heavy musk thistle infestation were chosen to follow plant growth from germination to senescence, determining how the musk thistle reacts to Oklahoma climate, timing of plant bolting and weevil infestations. To avoid inaccurate data from transplant shock only plants germinating in the field were used. Local conditions such as crowding, other plants (e.g. grasses), presence or lack of water, and weather conditions were allowed to take their natural course in these areas. Plants acting as true biennials and winter annuals were followed separately.

At each location, 100 plants were selected and marked. Seedlings selected were less than 75 mm in diameter with fewer than five leaves. Only vigorous plants were chosen, rejecting those appearing weak, damaged or otherwise unfit. Crowding or unique local conditions were noted. During the growing season rosette diameter in mm and number of leaves on each plant were recorded weekly. Damage from insects, cattle or weather conditions was noted for affected plants. Measurements were discontinued during winter dormancy and restarted when growth resumed in the spring.

The date and rate of bolting, first bloom, number of heads, head weevil presence in spring, dates of oviposition and senescence per plant were recorded. Whereever possible, the cause of plant death was recorded. When the plants attained normal senescence, plant height, stem diameter, number of heads, head location were recorded, and heads removed for laboratory analysis. In the laboratory, head diameter in mm was measured, head weevil pupal chambers counted, and the presence or absence of seed recorded. Additional factors monitored at different sites included seed counts in uninfested thistle heads, thistle survivor rates in overcrowded areas, and secondary pests in musk thistle plants. Each of these factors will be discussed with their location. Two locations were chosen to compare widely different growing conditions. One area had good pasture cover, while the other consisted of primarily bare ground.

Major County. An unused area between two fields with very heavy musk thistle infestation and few head weevils, located five miles west and 3 miles north of Lahoma OK, on county road N2720 between county roads E400 & E390 was chosen for observation. The owner allowed unlimited access to the land from May 2000 to July 2001. He actively participated, voluntarily cancelling all planned herbicide treatments on his property to prevent damage to the experiments and fencing the area (0.21 ha) to prevent cattle damage once heads were present.

The Lahoma site is situated between an alfalfa field, to the north, and winter wheat, to the south and west. Cattle have access to the land when the wheat is grazed and trample any grass present leaving bare, hard ground over most of the site. The adjacent wheat field is on a slope and highly erodible. A large gully running south to north following the slope divides the area. Three large cottonwood trees provide shade to the north side for 5-6 hours a day. See Fig. 3.1 for the site map.

In May 2000, 100 spring germinated seedlings north of the berm both east and west of the gully were marked. During July 2000, four plots of one square meter (meter square study) were marked out in very crowded areas. All spring-germinated plants were counted and the area was left undisturbed until plant senescence, when surviving plants were counted and measured.

Lack of rain delayed fall thistle germination until the first week in November 2000. On November 10, 100 seedlings were marked split between two areas. Seventy plants were chosen south of the cottonwood trees and thirty northeast of the gully. Seedling emergence was very thick, so two additional one meter plots were marked and plants counted in November and at senescence.

With very few head weevils at this site, mature uninfested thistle seed heads were collected to count the number of seeds produced. Heads were covered with a cotton bag and secured with a twist-tie when blooms began to fade. Eleven plants were chosen for head collections, with head position labeled according to McCarty (1982). Additional heads of various sizes were gathered at random and bagged to prevent loss of seeds. All selected heads matured on the plant, were collected at senescence, and stored in paper bags to prevent moisture accumulation and mold.

Payne County. A heavily infested pasture of approximately 16.2 ha, owned by the First United Methodist Church, on Sangre Bend Road at the northwest edge of Stillwater, OK was chosen as the second area. This pasture consists of various grasses, weeds, blackberries, and occasional trees. Cattle are present part of the year. Pasture management is done by the renter to maintain good feed for his cattle, but he expressed frustration with the musk thistle density

(Personal Communication). Thistle plants are infested with head weevils. Thistle density varies throughout the pasture, clear areas mixed with dense patches of thistles.

In May and November 2000, 100 spring and 100 fall seedlings respectively were marked and measured using the same procedure as the Major county site. On June 12, 2000 the pasture was sprayed with Grazon P+D, with all marked plants dying within two weeks. In April 2001, a second location, the junction of Airport & Jardot Roads, at the northeast edge of Stillwater was chosen as a replacement. The ditch, twenty feet by 0.5 mile, was heavily infested with musk thistle and head weevils. Plant density was 4.13/ m^2, 384/1000 ft^2 (0.01 ha) or 38400 plants/ha. Fifty plants, approximately the same diameter as spring germinated plants in Major Co., were selected April 12, 2001 to replace the dead plants from Sangre Bend.

Results

Major County. GENERAL PLANT GROWTH. The area studied was approximately 0.21 ha with plant densities varying greatly. Individual plant growth also varied depending on the degree of crowding. Spring germinated plants added new leaves at a rate of one to four per month at even intervals throughout the summer and fall. Growth in the diameter of rosettes was sporadic, with severe grasshopper damage occurring several times during the course of plant life. Grasshopper damage during the weeks of July 5-20, 2000 reduced rosette diameter by over half in approximately 75% of the plants on site. The majority of plants recovered quickly. During the hot dry weeks of summer, rosette growth was temporarily halted. New leaves emerged from the rosette forming a dense center, but did not elongate until after rain fell in October. Plants entered dormancy in December 2000.

Bolting for both spring and fall seedlings initiated during the second to fourth weeks in April, 2001. Maximum plant height was reached within seven to nine weeks after initiation of bolting. Fig. 3.2 shows the average weekly and daily bolting rate in mm for each location and germination time. Rosette growth ended once bolting began. As the flower stalk grew, rosette leaves dried and dropped off, leaving a thick mat covering the ground. Bloom rate varied by plant, with large unmarked plants on the edge of the site continuing to produce new blooms into July of 2001. As plants began to senesce, and shrink, leaves began to dry from the bottom upward. Seeds were released over a short period of time with the majority falling near the base of the plants.

SPRING GERMINATED PLANTS: Germination occurred from late April to early June with densities ranging from approximately 12-108 plants/m^2 (~120,000-1,080,000 plants/ha). Selected plants germinated during the last two weeks of May 2000. Of 100 plants, 40 survived to bloom, overcrowding or grasshopper damage killed 48 plants, and 12 plants were lost over fifteen months. Overcrowding affected 78% of dead plants, large vigorous plants shading smaller ones, or seedlings in very close proximity competed for resources, and in either situation small plants died.

After an ice and snow storm on Dec. 10, 2000, plants entered dormancy. Plant monitoring resumed on March 10, 2001. During the entire month of April initiation of bolting occurred and maximum height was reached within seven to ten weeks. The first buds appeared between four and six weeks after initiation of bolting and blossomed two to three weeks later.

A severe wind storm damaged the site on May 27, 2001. Maximum winds were 37.7 mph with gusts over 70 mph. Plants were broken, tangled and mature head were torn off. Senescence began in late June with most plants dead or dying by July 2001. Plants were harvested and head collected. Seeds were released as the plants matured so none were available to count. Head weevils, *Rhinocyllus conicus* Froelich., released on site May 10, 2001 were not present in collected seed heads.

FALL GERMINATED PLANTS: Germination was delayed by dry weather in September and October, 2000. Heavy rains in late October totaling 6.33 inches triggered germination with plants large enough to mark and measure by Nov. 10, 2000 in densities ranging from approximately 155 - 400 plants/m^2 (~1,550,000-4,000,000 plants/ha). Seedlings grew for five weeks before entering dormancy, with ninety-five plants survived dormancy. Plants resumed growth and bolting paralleling the schedule of spring-germinated seedlings. Although bolting dates were similar (Table 3.4), fall seedlings bolted at a slower rate than spring seedlings (Fig. 3.2).

Eighty six fall-germinated plants bolted and produced heads. Nine plants did not bolt, remaining as rosettes until they died from shading by surrounding plants. Crowding at the site produced thin stems; 77% of plants had a stem diameter nine mm or less. Variegated cutworms, *Peridroma saucis* (Hubner), were present in large numbers during June 2001. Larvae fed on the tender tops of thin flower stalks, causing them to break. Spring-germinated plants with larger stem diameters were not as severely affected, holes in the stem calloused over but did not break. Thirty six of the fall plants broke, and all of them initiated lateral stems producing heads.

Smaller fall plants produced fewer heads than the larger spring plants. Seventy-six percent of plants produced one or two heads, 75% had a diameter of less than 15 mm, and 32% of plants produced mature seed. (Fig. 3.3b) Seed on the remaining plants was immature, black and shriveled. (Fig. 3.3a)

Crowded plants were unable to withstand heat and dry conditions compared to the more robust spring-germinated plants. Rosettes and leaves on flower stems of fall-germinated plants dried earlier than those germinated in spring. The majority of thistle plants had three or fewer leaves near the top of the stem by the time of senescence. Plants germinated in the fall reached senescence a minimum of two weeks earlier than those that germinated in spring.

METER SQUARE PLOTS. A total of six plots, each one meter square, were laid out to monitor plant survival. (Fig. 3.1) As crowding increased, plant survival decreased and breakage from insect and storm damage increased. Table 3.2 provides survival rates for all six plots. Intact plants had one to two heads per plant. The number of heads on plants with broken stems depended on the number of lateral stems initiated. Heads were measured on only the fall plants. Wind storms broke off a large number of mature heads before spring-germinated plants could be harvested. Plants germinated in the fall lost very few heads during the high winds. Ninety-eight to one hundred percent of spring plants produced heads. Fall-germinated plants: in the east plot (13 plants) bolted but did not produce heads, 54 (52%) produced seeds, and 3 plants produced mature seed; in the west plot 26% of plants bolted but did not produce heads, 27 (13.5%) produced seed, none of it mature. As crowding increased; plant size, number of heads, and mature seed decreased. Figure 3.3 shows the difference between mature and immature seed.

SEED COUNTS. All bagged uninfested seed heads were kept dry until processing. In the laboratory the pappus was removed and seeds released. Head diameter was measured in mm at the base of the receptacle. Seed numbers for each head size were averaged. Fig. 3.4 shows the number of seeds per head/per mm in both the randomly picked heads and by plant position. Heads counted by plant position show that terminal heads (T, A, B, C, D) were consistently larger and had a larger number of seeds than heads on the interior of a branch (Fig 3.4). Analyzing the seed counts with PROC MIXED (SAS Institute 2000) verifies larger heads have more seeds per mm diameter (df = 99, r^2 = 0.7304, p = <.0001). These results are consistent with those reported by McCarty (1964) and Kok (1984).

Payne County. SANGRE BEND. Pasture plants listed previously were allowed by the renter to grow undisturbed to approximately 0.3-0.4 m in height until June 2000 when cattle were released into the area. One hundred plants, marked during the last week of May 2000, grew very slowly. Grasshoppers consumed new leaves immediately following emergence from the crown. Pasture areas with dense growth crowded thistle seedlings, leaving them weak and spindly. On June 12, 2000, the renter sprayed open areas of the pasture with Grazon P+D. He sprayed as close to trees as possible with his equipment but was unable to reach the entire pasture (Personal Communication). Marked plants were within the areas sprayed and all died within three weeks. Some seedlings in dense pasture areas were able to survive. By mid-June much of the grass had reached 0.5 m in height and appeared to prevent the treatment from reaching all of the seedlings at ground level. Bolting thistles were unaffected by the herbicide, Head weevils were present in large numbers and appeared uninjured. The site was left undisturbed until germination of fall seedlings. Fall-germinated seedlings emerged after rain in October and 100 were marked similar to those in Major Co. Approximately five weeks after germination the plants entered dormancy. Growth resumed in March 2001. Ninety-seven plants survived dormancy. Initiation of bolting did not begin until mid-May and continued through June. Fig. 3.2 shows the bolting rates obtained at all sites. Twenty-nine plants bolted, all were short (average height 0.5 m) and spindly, and no mature seeds was produced.

Sixty-eight plants did not bolt, unable to compete with the faster growing pasture grasses. Non-bolting plants did not leave the juvenile leaf stage and progress to the mature leaf stage. Fig. 3.5 depicts the difference between juvenile and mature leaves on the same plant at different ages. During spring and summer growth periods plants struggled to grow and were frequently damaged by grasshoppers or cattle. Damage from cattle was generally minimal and plants recovered quickly; grasshoppers caused permanent damage by consuming biomass. On June 15, 2001, the renter sprayed the pasture with a "heavy dose" of 2,4-D herbicide. Plants 1-20 and 80-100 were outside the primary spray area and were unaffected. Unbolted plants 30-70 were already weakened from competition and died within three weeks. Seedlings from spring 2001 were variably affected depending on location. The experiment was ended in August when the remaining 12 plants were dying.

Herbicide damage was evident when surviving plants from 2000 began to bolt. Bolting was delayed until after adult head weevil activity was finished. All plants were shorter and stockier than normal, but had uninfested heads. Tall pasture grasses appear to have compounded the damage by competing better for nutrients, space and light than ground level seedlings.

AIRPORT & JARDOT. Marked plants initiated bolting the second week of April. The rate of bolting (166.2 mm/week or 23.7 mm/day) was similar to spring-germinated plants from Major Co. (Fig. 3.2). Lower thistle densities at this site allowed plants to grow larger and produce more heads. Grass and low-growing annual weeds were present but the thistles were able to compete with these plants.

Head weevil adults were present as soon as the stem emerged. Head weevil eggs were present in large numbers on flower buds within 10 days of adult emergence from hibernation. Adult weevils were present approximately 5.5 weeks. Buds initiated three weeks after bolting, and continued to be produced until senescence. Head weevils infested all terminal and most secondary heads. Tertiary and quaternary heads were infested if they developed while weevil adults were present. Senescence began the last week of June 2001, progressing rapidly.

Larvae of *Homeosoma elactellum* (Hulst), the sunflower moth, were present in most heads located on lateral 'B' and lower (McCarty 1982). Damage to heads depended on the number of sunflower moth larvae present. Larvae normally feed on pollen and florets of sunflower plants and begin feeding on seeds in the third instar (McLeod 1994). The same pattern was found on musk thistle. Larvae feeding on heads left large tangles of webbing in the pappus (Fig. 3.6a). Webbing tangled the seed head and prevented seeds from dispersing normally. Small heads did not provide enough pollen for the larvae, causing them to feed on any developing seeds and receptacle tissue (Fig. 3.6b), thereby totally destroying seed heads. The sunflower moth did provide thistle control where present during 2001.

PLANT DENSITY. Plant density affected thistle size and number of heads produced. Table 3.3 compares the number of heads per plant to density per square meter and 1000 ft^2 (Lowest densities at the Major Co. site were used). Spring-germinated plants at the Airport & Jardot site were 1/3 the lowest density in Major county. Although the rosettes were approximately the same size when marked, the plants located at Airport & Jardot produced more heads sooner. The large rosette size and number of leaves shaded the soil preventing other seeds from germinating. By mid-June rosette leaves dried and crumbled leaving bare soil ready for newly shed seed. The result is a circular system with other plants increasingly excluded until only musk thistle is present.

Extreme crowding at the fall germination site in Major county prevented plants from producing substantial numbers of mature seed. In the two meter square plots, out of 303 surviving plants, only three produced mature seed. After excluding all other plants, the thistles competed with each other too well, preventing some plants from bolting and mature seed production in the highest densities.

GROWING DEGREE DAYS. Tying thistle growth stages to temperature data was difficult. Currently, no data exists on growing degree day (GDD) calculations for musk thistle. Research from Virginia is frequently quoted, however, as shown by Table 3.1 their climate is considerably different from Oklahoma. *Plants in Virginia bolt in late April, bloom in late May and head* weevils emerge from the soil in early May (Surles et al. 1974). A cooler summer allows plants to bloom into August. In Oklahoma, plants bolt in early to mid April, bloom in early May, weevils emerge in late April and senescence occurs in July. Plants emerge from dormancy in late winter, as early as the end of February or early March.

Weather data from the Lahoma (Major Co.) and Stillwater (Payne Co.) monitoring stations of the Oklahoma Mesonet (Brock et al. 1995) were used to calculate GDDs from January 1 using a base temperature of -1.1^{O}, 1.6^{O} and 4.4^{O} C. 2000 was a warmer season than 2001 and visual observations showed thistles blooming approximately one week later in 2001. A comparison of known dates in 2001 to estimated dates for 2000 was done. Table 3.4 gives GDDs for the end of dormancy, bolt, bud, & bloom times for 2000 & 2001 in both Major and Payne counties Using a base of -1.1° appears impractical, since air temperatures are below freezing. Bases of 1.1° or 4.4° fit better because plants will continue to grow at very low temperatures and the air is above freezing. In 2001, 209 GDD were obtained at the 1.1° base and 74 GDD at 4.4°. Either method illustrates the ability of plants to grow at low air temperatures. Additional studies should be conducted to confirm the number of GDDs needed to break dormancy. The number of GDDs for bolting was quite variable (up to 200 GDD's). In contrast, the blooming period was more consistent with less than 50 GDD's difference. Bud initiation using a base temperature of 1.1° and 4.4° were nearly identical at Lahoma and varied less than 120 GDD's apart at Stillwater.

Soil temperatures for these dates are noted in Table 3.4. Larger differences in soil temperature at the end of dormancy show that, at this time, plants are responding to air temperature rather than soil temperature. The initiation of bolting and bloom times occurred at similar soil temperatures for both years. Bud initiation also does not appear to be related to soil temperature either year. Based on these observations, it appears that musk thistle plants appear to respond to air or soil temperatures differently during distinct life stages.

FACTORS AFFECTING HEAD NUMBER. Larger numbers of heads/plant have the potential to increase the seed load in the soil seed bank. The following factors were analyzed in SAS using the Correlation function to determine which may have the greatest influence on head numbers: Number of leaves at bolting, rosette diameter at bolting, final plant height, number of heads, and final stem diameter. Collectively all factors influenced final head counts ($P \leq .0001$). The highest correlation ($r^2 = 0.80$) was final stem diameter at the Buller farm and Airport & Jardot ($r^2 = 0.82$). (Table 3.5) When as little as six inches of stem has developed, it is possible to determine if the final stem diameter will be thick or thin. A plant with a large stem diameter has potential to produce greater numbers of heads. Fall plants from the Buller site were so overcrowded that no one factor had a significant relationship to head number.

Discussion

Following the development of musk thistle plants in Oklahoma for a full generation shows a growth pattern different from Virginia (Surles et al. 1974). Bolting and blooming are approximately three weeks earlier and hot summer weather induced senescence six to eight weeks earlier than in Virginia. Head weevil adults emerge from the soil two weeks earlier than Virginia, but remain active four to five week in both locations (Surles and Kok 1977). These differences justify the need for rewriting control and weevil release/recapture recommendations. Accurate timing of thistle growth and weevil activity will allow growers to modify herbicide spray programs, mowing, and weevil collection/release programs. The improperly timed herbicide application at Sangre Bend in 2000 disrupted the bolting/oviposition cycle of thistles and weevils, leading to uninfested seed heads.

Giving growers a reliable time frame to determine appropriate times for herbicide application, mowing, and weevil releases has been an important factor in this study. GDDs verify musk thistle's ability to resume growth as early as the end of February. Bolting, an important life stage in control measures, is more closely tied to soil temperatures than the resumption of growth. Growers who monitor meteorological data will be able to predict bolting and time herbicide applications. Correlation of growth factors also provides valuable data. It is possible to predict if plants will be able to produce large numbers of heads. Final stem diameter is the main determining factor for head number. Stem diameter, evident early in bolting, allows growers to make last minute treatment decisions. Plants with thin stems will be less likely to produce large numbers of heads so herbicide may be not be needed.

Musk thistle's ability to survive depends to some extent on the site. Plants are able to thrive through Oklahoma's hot dry summers, insects damage, and moderate crowding. Extreme crowding caused by thistles themselves, (Major county) reduced both plant vitality and mature seed production. Competition from pasture grasses at Sangre Bend prevented fall-germinated seedling transition from juvenile to mature plants and seed production. Lower plant density at Airport and Jardot gave thistles a competitive edge, growing larger and producing more heads than the Major county and Sangre Bend site.

Head weevils were present in the Payne county sites, but not the site in Major county. Musk thistle growth is not affected by head weevil feeding. Phytophagous insects did cause plant damage, though generally not plant death. Plants recovered from the majority of insects damage very quickly. Variegated cutworm moth larvae had the most impact. Even though damaged fall–germinated plants initiated new lateral branches, the heads did not produce mature seed. Surviving grasshopper damaged plants produced mature seed.

Following musk thistle plants through additional generations will verify these results, providing a more accurate model of growth patterns in Oklahoma. Verifying GDDs, stem diameter correlation to head number and, density related seed counts will facilitate constructing thistle management plans for growers use.

Acknowledgments I am grateful to Mr. Leroy Buller, Major Co., for giving me access to his land and providing assistance with this study. Thank you also to the First United Methodist Church, Stillwater, OK and the City of Stillwater for allowing me to use their land. I also appreciate the help of Penny Potter for tramping through thistles with me, data recording, and processing thistle heads.

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State	Mean days with temp. below 32° F.	Mean days with temp. above 90° F.	Average wind speed in mph	Average annual precipitation	Month of highest rainfall
California	17.5	94.4	6.9	22.6"	Nov.-Jan.
Missouri	103.5	37.5	10.1	41.3"	evenly spread through year
Montana	166.5	22	10.5	13.2"	Apr.-Sept.
Nebraska	176.5	37	9.7	18.8"	May-July
Oklahoma	75.5	70	11.25	36.9"	Apr.-June & Oct.-Nov.
Virginia	89.5	25.5	7.6	41"	evenly spread through year

Table 3.1. Climatic differences between Oklahoma and other states conducting musk thistle research. Data consists of 30 year averages (1961-1990) from the National Climatic Data Survey.

Location	starting #	# survived	% survived	# bloomed	% bloomed*	# broken	# rebloom**
Spring- Cow path, west	79	62	78	61	98	6	5
Spring- Cow path, east	98	48	49	48	100	8	8
Spring- N. fence, west	93	50	54	50	100	11	11
Spring- N. fence, east	96	49	51	47	96	2	0
Fall- north	155	103	66	90	87	20	12
Fall- south	382	200	52	147	73	31	22

Table 3.2. Meter square plot plant survival rates from germination to senescence
* % bloom figured from # survived, **# rebloom is from # broken plants

Locality	Plants/m²*	Plants/1000 ft²*	Ave. # heads/plant
Payne Co., Airport	4.13	384	15.9 ± 1.06**
Major Co.,Spring	12	1,116	4.5 ± 0.09
Major Co., Fall	155	14,415	2.2 ± 0.05

Table 3.3 Head numbers per plant by location related to the density of plants/1000ft^2
* actual site counts
** SEM for ave. # heads/plant

Location	Date	Growing Degree Days in °C.			Soil Temp in. °C @ 5 cm *	
Lahoma		-1.1	1.1	4.4	Temp.	Diff
End of dormancy	2/22/00	503	308	160	11.1	
	3/1/01	423	209	74	1.9	9.2
Bolting	4/7/00	1478	1049	682	13.3	
	4/11/01	1264	846	514	15.6	2.3
Bud initiation	5/2/00	2149	1600	1112	16.3	
	5/9/01	2164	1606	1134	21	4.7
Head	5/16/00	2667	2048	1490	21.4	
	5/23/01	2732	2104	1563	20.1	1.3
Stillwater						
End of dormancy	2/22/00	622	410	234	11	
	3/1/01	497	268	118	5.2	5.8
Bolting	4/10/00	1766	1314	902	14.3	
	4/17/01	1591	1127	746	13.8	0.5
Bud initiation	4/24/00	2182	1661	1179	17	
	5/1/01	2078	1544	1094	18.7	1.7
Head	5/8/00	2676	2085	1533	21.8	
	5/15/01	2651	2047	1526	22.2	0.4

Table 3.4. Growing Degree Days and soil temperatures in 2000 & 2001
* Data obtained from the Oklahoma Mesonet

	Buller farm	Airport & Jardot
# leaves at bolt	0.71025	0.70123
Rosette dia. @ bolt	0.72229	0.78786
Final height	0.58784	0.61056
Final stem dia.	0.80407	0.82321

Table 3.5. Correlation of plant factors to the potential for head production. All values have a p-value of $\leq .0001$.

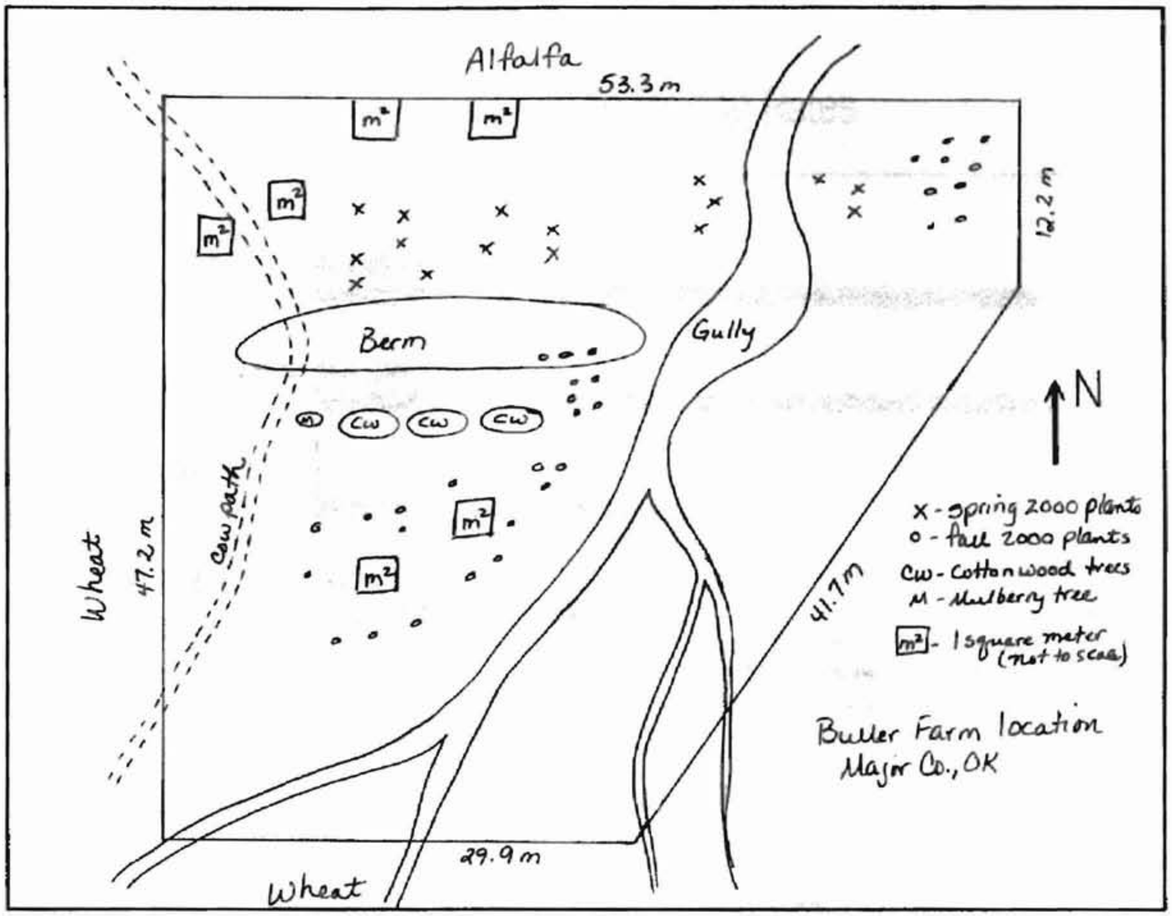


Fig. 3.1 Map of Buller farm site (not to exact scale) plant locations approximate

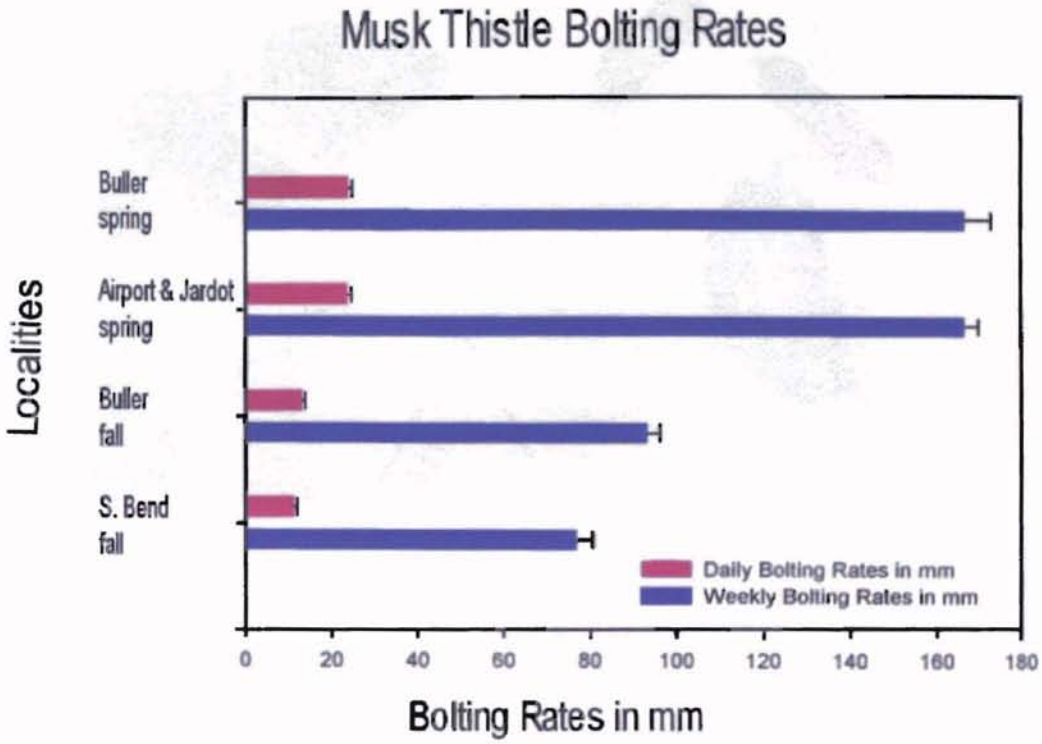
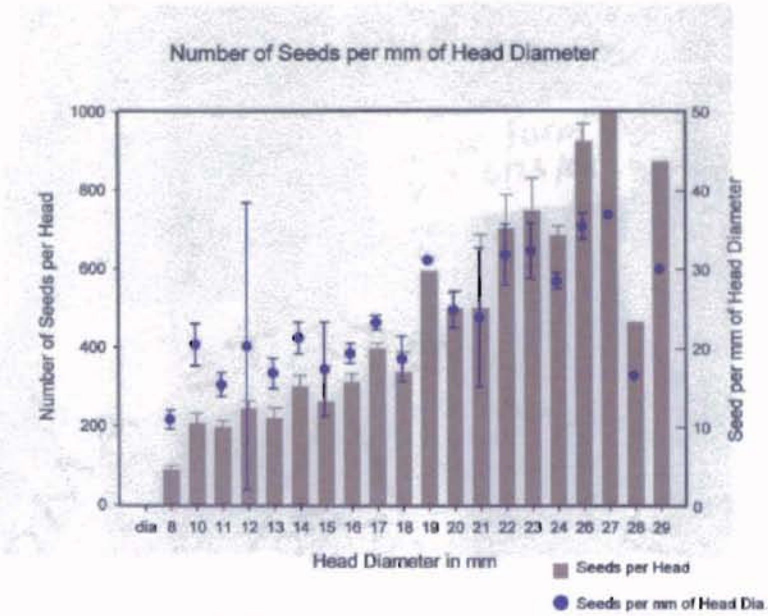


Fig. 3.2. Mean ± SEM of bolting rates in mm at each location.

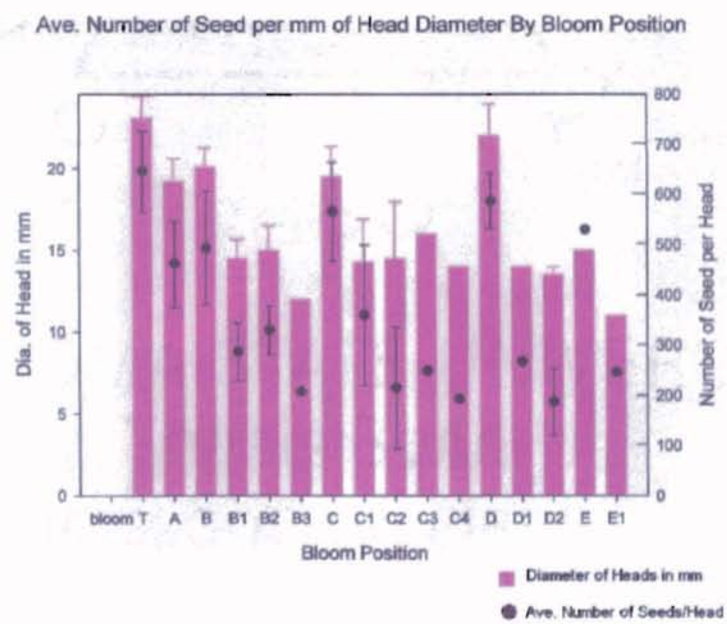
a) immature thistle seed

b) mature thistle seed

Fig. 3.3 Comparison of immature and mature musk thistle seed



a) Seed numbers per thistle head by head diameter and per mm head diameter



b) Seed Numbers per mm of head size by position on plant

Fig. 3.4 Mean ± SEM for mature seed numbers per head by head diameter and head position. Data points without SEM bars did not have enough samples

a) Juvenile leaf form 6/26/2000

b) Mature leaf form 3/10/2001

Fig. 3.5 Musk thistle rosettes, juvenile and mature leaf forms

a) top view, webbing and frass tangling the pappus

b) cut view, webbing and frass in pappus with receptacle damage

Fig. 3.6 Sunflower moth larval damage to thistle heads

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Chapter IV

Ovipositional Preference of *Rhinocyllus conicus* Froelich, the Musk Thistle Head Weevil, (Coleoptera: Curculionidae) on the Blooms of *Carduus nutans*, the Musk Thistle (Asterales: Asteraceae)

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Abstract Oviposition site preference for *Rhinocyllus conicus* Froelich, the musk thistle head weevil, on *Carduus nutans* L., the musk thistle, was studied to provide growers a fast method of checking weevil infestations. Thistle heads from entire plants were labeled individually, receptacle diameter measured in mm and the number of eggs counted. Head locations were determined to be either top v/s bottom or outside v/s inside. In 2000, preference was shown for outside v/s inside heads (P-value <.0001). A slight preference was shown for top v/s bottom (P-value 0.1278). In 2001, locations had been weevil infested for six or more years with fewer larger weevil populations and fewer available oviposition sites. No preference was shown for specific plant locations and P-values for in v/s out were 0.7270 and top v/s bottom 0.3815. Oviposition preference is a valuable tool in infestation years three to five while weevil are establishing. Checking top outside heads for egg numbers will allow growers to determine levels of weevil infestations. After six years ovipositional preference is a moot point.

Key Words *Rhinocyllus conicus*, *Carduus nutans*, musk thistle, head weevil, oviposition

Introduction

Musk thistle, *Carduus nutans* L., is a noxious weed with many extensive stands in Oklahoma. Starting in 1991, *Rhinocyllus conicus* Froelich, the musk thistle head weevil, was released in the northeastern part of the state as a biological control measure (Stritzke, et al. 1999). Longterm monitoring of weevil activity in Virginia and Missouri determined that six to ten years of weevil infestation are required for optimum effectiveness (Kok and Surles 1975; McDonald et al. 1989).

If a limited number of oviposition sites is available, head weevil females will oviposit excessive numbers of eggs on the bracts of terminal heads (200+/head). When oviposition sites in a location have reached a saturation point, female weevils will search for new areas (Rees 1991), with emigration, at times, exceeding 8 km./year following the prevailing winds, (Kok and Surles 1975; Rees 1977). When head weevil numbers reach the saturation point, collecting and transferring them to new locations extends the control area with little additional cost (McDonald et al. 1989; Stritzke, et al. 1999). Determining when previously released head weevil populations are large enough to begin redistribution requires monitoring. Reducing weevil numbers by collection for redistribution before weevils are established can slow thistle control at the original release sites.

One important aspect to successful biological control is providing growers and landowners with tools to monitor progress on their land. The monitoring system must be fast and easy to use for the greatest success. Cutting thistle heads open at various times of the year is an effective monitoring method. This system assumes the person responsible for monitoring has time to collect heads, magnifying equipment needed to count very tiny first instar larvae early in the season, and knows what to look for.

Egg density on musk thistle heads affects the number of emerging adults. Large terminal heads may have 200-300 eggs, but only 20-45 will survive and emerge as adults (Rees 1991). Food availability appears to be the major factor determining larval survival to adulthood and their final body weight. Overcrowded heads lead to head abortions (early head death) resulting in fewer, lower weight adults (Dowd and Kok 1981). In medium-sized heads (17-20 mm.) 8-13 larvae survived to the adult stage, with large heads (25-30 mm.) having 13-20 adults survive. Infestations at this level destroy all seeds in the heads of musk thistle (Roduner 2001).

Knowing the approximate number of larvae that can reach adulthood in a particular head size allows for accurate assessments of potential infestation based on eggs present on the bracts of heads. Any eggs over the number of larvae that can be supported to adulthood will not survive. Previous studies have measured egg density as mean eggs/head (Kok 1974; Kok and Surles 1975; Surles and Kok 1977). To equalize measurements across the thistle plant this study looked at mean eggs/mm of head diameter to determine oviposition preference. The goal of this study is to provide growers and landowners with a fast monitoring method using egg numbers and their location on the plant to determine infestation during the early years after weevil releases.

Materials and Methods

In Oklahoma, during the summers of 2000 & 2001, mature musk thistle plants were taken from heavily infested pastures. Collections were made in nine counties: Adair, Cherokee, Craig, Delaware, Noble(3), Nowata, Osage, Payne (2), and Washington. One hundred and eighty- eight plants were removed from a total of twelve sites. Thistle infestations in pastures were a minimum 0.5 ha to over 20 ha in size. Head weevils were present in moderate to large numbers at all sites. Both large and small plants were selected to represent the range of sizes present at each site. To avoid late-developing, uninfested heads, plants were collected within two weeks of the cessation of oviposition by head weevils. Plants missing multiple heads or lateral branches were rejected. Thistle plants were removed at ground level, height measured in mm., and number of heads per plant recorded. Egg numbers and their position on the plant were studied, and comparisons were made for top/bottom and inside/outside of the plant, along with large/small (by numbers of heads) and tall/short plants.

Each head was removed and bagged separately. Head position on plants was numbered according to McCarty (1982), then frozen until processed. A total of 1,463 heads were analyzed. The diameter of each head was measured in mm. at the receptacle base. Eggs on the underside of bracts were counted and recorded.

All thistle heads from the main terminal (T), and each major lateral branch (A, B, & C) were considered to be on the top of the plant. Heads from D and lower represent the bottom of the plant. Terminal heads T, A, B, & C and the first head after A etc., (A_1, B_1, C_1) were considered to be on the outside of the plant. Inside heads were B_2, B_{2a}, and B_{2a1} etc. Data were analyzed using PROC MIXED and PROC REG in SAS version 8e, to determine eggs/mm. of head diameter, ovipositional preference for location on the plant, number of heads per plant and plant size.

Results

In 2000, head weevils had a significant preference for outer (terminal) parts of branches over the inner branches (p= 0.0001). Plant tops were only slightly preferred to bottoms (p=0.1278). Head weevil eggs/mm of thistle head diameter increased in 2001 by 32-73% depending on head location. There was no preference, in 2001, for any one location on the plant. Table 4.1 gives a summary of both years data including percent increase of egg numbers from 2000 to 2001.

To determine head weevil preference for tall v/s short plants and a large number of heads v/s small number, plant height, head number, and eggs/head were analyzed using analysis of variance (ANOVA) and multiple regression with backward elimination. The analysis was done over all plants, irrespective of collection site, providing a more accurate model of weevil-plant interactions. In both analysis, the number of heads was a more important factor than plant heights. Fig. 4.2 shows p-values of the number of heads were <.0001 in all steps. When all factors were included (r^2 = 0.803) , for every additional head, 20 eggs were added to the total. After performing the backward elimination, heads were the only important factor ($r^2 = 0.776$), with 9.27 eggs added for each additional head.

Discussion

An additional year of weevil infestation can account for the increased egg numbers in 2001. Previous studies have shown that within four to six years after infestation, weevil populations increase sharply, with the "explosive" phase at about year six. At this point the weevil population explodes and musk thistle populations "crash" or decline rapidly within two to three years resulting from the reduction of available seed in the soil seed bank (Kok and Pienkowski 1984). This was observed in Oklahoma during 2001(Roduner 2001). As the weevil population increased, the number of eggs/head increased and the lack of available sites for oviposition made preference sites a moot point.

During the early years of infestation, ovipostional preference is more pronounced. Counting the number of eggs/mm head size confirms previous studies using mean eggs/head, showing that terminals were the preferred oviposition site. These heads are not only the first available, but also the largest. With previous studies showing that as few as four to five larvae/head cause a reduction in seed production, and nine to ten larvae/head reduce seed production to almost zero (Rees 1991; Surles and Kok 1978). Therefore, numbers of eggs present on the bracts can serve as a good predictor for subsequent larval populations. Effective egg numbers will depend on head size. As previously stated, in medium size heads (17-20 mm) 8-13 larvae survived to the adult stage destroying 100% of seeds, and large heads (25-30 mm) require

13-20 adults for the same level of destruction.

Ovipositional preference is a good tool for growers to use in the early years of weevil infestation. During the first two years insufficient numbers of weevils were present to adequately determine their establishment. From the third to fifth year, populations increased dramatically (Surles and Kok 1978), making positional preference a quick and easy way to determine levels of weevil infestation. After year five, the numbers of weevils increased so dramatically that they no longer exhibited a preference in oviposition location, using every available head, and in some cases even the stems below the heads (Shorthouse and Lalonde 1984).

An estimate of twenty to twenty-five eggs/medium head and thirty to thirty-five eggs/large head on the terminals and first lateral head represent a sufficient food supply to provide larvae the ultimate opportunity to reduce seed numbers. Examining only these heads by quickly looking at the underside of the bracts can be done in less than five minutes per plant. Plants with more heads attract a larger number of weevils for oviposition than a particular height plant. Checking approximately twenty plants with the largest number of heads from the edges and middle of a stand gives a rough estimate of weevil numbers and informs the grower about how rapidly establishment is occurring.

Acknowledgments Thanks goes to Tererai Nyamanzi and Penny Potter for processing the thistle heads.

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Year	Plant Region	Eggs/mm	Comparison	P-value	% change
2000	Bottom (B)	0.3320			
	Top (T)	0.3905			
			T v/s B	0.1278	
	Inside (I)	0.2093			
	Outside (O)	0.4529			
			I v/s O	<.0001	
2001	Bottom (B)	0.6124			46
	Top (T)	0.6871			43
			T v/s B	0.3815	
	Inside (I)	0.7821			73
	Outside (O)	0.6610			32
			I v/s O	0.7270	

Table 4.1 Comparison of top v/s bottom and inside v/s outside oviposition preference with percent change from 2000 to 2001.

ANOVA	r^2	Factor*	Parameter Est.	p-value
all factors	0.803	HGT	-0.201 ± 0.129	0.1262
		HEADS	20.852 ± 4.492	<.0001
		HGT2	0.0001 ± 0.00006	0.084
		HEADS2	-0.058 ± 0.035	0.103
		HGTHEADS	-0.007 ± 0.002	0.021
Elimination step 1	0.794	HEADS	16.54 ± 3.581	<.0001
		HGT2	0.000 ± 0.00001	0.2865
		HEADS2	-0.044 ± 0.035	0.2006
		HGT	-0.004 ± 0.002	0.0802
Elimination step 2	0.789	HEADS	15.279 ± 3.387	<.0001
		HEADS2	-0.056 ± 0.033	0.0918
		HGTHEADS	-0.002 ± 0.002	0.1548
Elimination step 3	0.781	HEADS	10.954 ±1.589	<.0001
		HEADS2	-0.034± 0.029	0.2492
Elimination step 4	0.776	HEADS	9.269 ± 0.659	<.0001

Table 4.2 Results of ANOVA and Backward Elimination in multiple regression analysis
* HGT- height in mm of individual plants, HEADS- number of heads on each plant, HGT2 & HEADS2- gives location and degree of angle for changes in regression line, HGTHEADS- interaction between height and heads.

VITA

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Candidate for the Degree of

Master of Science

Thesis: ESTABLISHMENT AND IMPACT OF THE MUSK THISTLE HEAD WEEVIL, *RHINOCYLLUS CONICUS*, AND THE ROSETTE WEEVIL, *TRICHOSIROCALUS HORRIDUS*, FOR CONTROL OF MUSK THISTLE, *CARDUUS NUTANS*, IN OKLAHOMA

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