University of Alberta

Defoliation and Grazing Effects on Canada Thistle and Forage Production in Pasture

by

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1. INTRODUCTION

1.1. Background

Canada thistle [*Cirsium arvense* (L.) Scop.], a perennial weed belonging to the Asteraceae family, is considered to be one of the world's worst weeds, and is problematic in many parts of the world, including Canada, the United States of America, Europe, western Asia, northern Africa, South America, New Zealand and Australia (Freidli and Bacher 2001; Ang et al. 1994; Donald 1990). It is estimated that Canada thistle (CT) covers a range of 9.77 million km^2 in North America, with a northern extent of 59ºN in Canada and south to 40ºN in the US (Donald 1990; Moore 1975). Reports indicate that CT was spread across 4 million ha of cultivated land in Alberta in the early 1960's, and in 1997 was present in 53% of all cereal and oilseed fields (Thomas et al. 1998; Alex 1966). CT was declared a noxious weed in Alberta in 1970 (Moore 1975). CT is present within nearly all types of plant communities, including cultivated land, rangeland, pastures, hay fields, lawns, gardens, roadsides, along railways, and in waste areas (Frankton and Mulligan 1987; Moore 1975). There has been extensive research regarding CT effects on annual cropland. There are few studies, however, that examine CT impacts on pasture, hayland and rangeland, even though many have recognized CT as a serious problem in perennial crops throughout the world, including the United States and Canada (Donald 1990; Moore 1975; Hodgson 1968). In Canada, CT is known to infest pasture, hayland, and alfalfa (*Medicago sativa* L.) seed fields (Moyer et al. 1991; Goodwin et al. 1986; Thomas and Wise 1983).

Canada thistle is a fierce competitor primarily due to its large and spreading root system. CT roots and root buds exhibit dormancy which allows them to survive adverse conditions including drought and freezing (Lauridson et al. 1983; McIntyre and Hunter 1975; Hamdoun 1970; Forsburg 1962). CT can regenerate from root fragments as small as 6-8 mm long (Prentiss 1989; Forsberg 1962), while root expansion can extend from 1.25-12.2 m in one season (Chancellor 1970; Bakker 1960; Hayden 1934; Rogers 1928). This amounts to a massive potential for aboveground shoot production, with 1.0 to 2.6 buds on 10 cm of root (McAllister and Haderlie 1985). Additionally, CT is known to thrive in many different soil types, including clay loam, sandy loam, sandy clay, silt loam, and sand (Moore 1975; Hodgson 1968), as well as saline areas (Donald 1990), and along water-logged areas (Hodgson 1968).

Many different strategies for the control of CT have been reported. Possible control methods include chemical, biological agents (insects and diseases), mowing, cultivation, timely fertilization, grazing and enhanced crop competition, and when used individually, vary in their effectiveness to control thistle (Donald 1990). As most of central Alberta pastures exist as a polyculture, dominated by long-lived perennial plants, integrated management appears to be the most appropriate system to achieve effective control of CT (Zimdahl 1999; Apple and Smith 1976). This combination of control is known as integrated pest (i.e. weed) management (IPM), and while individually each control method is incomplete, together they can cause the weed population to decrease rapidly (Hoeft et al. 2001; Jordan 1996; Pester et al. 1996). Despite this, little is known about the specific effectiveness of defoliation regimes, as determined by grazing systems, on the abundance of CT in pasture environments.

The presence of CT alters competitive patterns between plants and the foraging behavior of herbivores. Herbivores often avoid CT because of their spiny morphology in favor of more palatable plants. The species that are preferred, and therefore grazed heavily, are disadvantaged compared to those avoided, facilitating a competitive advantage for the less stressed species (Heitschmidt and Stuth 1991). CT plants that are avoided become larger and more competitive, reducing the amount of resources available to either defoliated or less competitive species. The availability of surplus carbohydrate that otherwise would have been used by surrounding plants allows for enhanced root growth, which will increase access to soil water and nutrients (Eissenstat and Caldwell 1988; Mueggler 1972). Conversely, if the CT plant is defoliated, the difference in the speed of regrowth shifts the competitive advantage to grasses.

Grasses have perhaps demonstrated the best ability to cope with defoliation among plant forms. This is because graminiod meristems are located at the base of the plant, which is often below grazing height (Youngner and McKell 1972). In contrast to graminiod species, forbs (including CT) have different responses to grazing. The growing points of these species are located at the top of the plant, thus, any type of grazing that removes top growth will remove apical vegetative buds. Under these conditions, it matters little how much green material is left on the plant, as new growth will have to be initiated from axillary buds (Crawley 1983). These differences in growth strategies indicate that defoliation can impact CT growth and spread.

Many permanent pastures have natural limitations to possible CT control methods. Landform may be restrictive to machinery access, limiting the use of mowing and chemical control. Regulatory restrictions to chemical application may also exist, such as near waterbodies or adjacent to or on organic farms. Biological competitive manipulation and controlled grazing of CT has been gaining importance for CT control because of environmental and economic concerns. However, the ability of biological agents to control CT has had limited success (DiTomaso 2000; Donald 1990; Trumble and Kok 1982), and to date, an effective biological agent has not been found. Goats and sheep have often been reported as effective control agents of CT in pastures (Popay and Field 1996; Thomson and Power 1993; Donald 1990; Amor and Harris 1975), however, in Alberta, these species of grazers are uncommon, while cattle are predominant.

Published data on using cattle to control CT does not appear to exist in western Canada. Cattle have been reported to provide some control of yellow star thistle (*Centaurea solstitialis* L.) (Thomsen et al. 1993). Cattle also seem to enter into patches of CT more effectively than sheep, and at higher stocking densities, may improve the control of treatments like mowing (Hartley and Thomson 1981). Exclusive studies using cattle defoliation to control CT have not been reported. Given that CT uses an avoidance strategy (spines) to withstand defoliation, and is susceptible to shading (Jordan 1996; Pester et al. 1996; Donald 1990; Pook 1983; Medd and Lovett 1978), it follows that if CT can be heavily defoliated, effective control might be achieved. In addition, because CT is a forb, and recovers slower than graminoid species after defoliation, defoliation of CT would shift the competitive advantage to the faster recovering grass species. As a result, original research is needed in western Canada to evaluate the impact of cattle defoliation regimes on Canada thistle in permanent pastures.

1.2. Specific Objectives

The specific objectives of this research were to:

(1) Review the information on competitive interactions, defoliation effects, grazing systems, and Canada thistle biology, ecology and control in pastures and hayland (Chapter 2),

(2) Evaluate Canada thistle and forage production responses to varied defoliation intensity and frequency of surrounding sward vegetation in Alberta pastures (Chapter 3),

(3) Investigate the ability of using rotational grazing systems with cattle to achieve direct control of Canada thistle, and evaluate the forage quality of Canada thistle (Chapter 4),

(4) Develop control recommendations (Chapter 5).

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2. LITERATURE REVIEW

2.1 Defoliation Effects

2.1.1 Grazing History

Among the most important factors influencing how an ecosystem responds to defoliation is its evolutionary history of grazing. A study conducted by Milchunas and Lauenroth (1992) tested 236 sites world-wide and compared species composition, aboveground net primary production, root biomass, and soil nutrients for grazed and ungrazed sites. For all variables, evolutionary history was one of the primary factors that dictated the sites response to grazing, commonly over-riding any other factor at each site. The history of grazing dictates how communities respond to defoliation (Hides 1978), as each species has differential responses to the removal of plant tissue.

Defoliation by herbivores affects vegetation both directly and indirectly. Grazing primarily impacts plant growth by directly removing leaf area, which subsequently reduces photosynthetic capacity (Briske and Heitschmidt 1991). This results in a reduction in the nutrients and carbohydrates available to the plant. Indirect effects associated with grazing are: alteration of energy flow, change in nutrient cycling, modification of microclimate, alteration of hydrologic properties, and destabilization of plant competitive interactions (Briske and Heitschmidt 1991).

When plants are described as grazing resistant, it generally describes their ability to prevent defoliation or survive in spite of defoliation. Growth forms of vegetation generally differ in resistance as follows: herbaceous monocots > herbaceous dicots > deciduous shrubs and trees > evergreen shrubs and trees (Archer and Tieszen 1986). Monocots are generally more grazing resistant because their apical and axillary meristems are located at the base of the plant, and are therefore less likely to be damaged by grazing. Woody plants and herbaceous dicots not only have terminal and lateral meristems that are easily damaged or removed by grazers (Briske and Heitschmidt 1991), but often have slower growth rates and low rates of resource mobilization (Chapin 1980), which are essential for replacing lost leaf tissue. As a result, woody plants and many dicots utilize avoidance mechanisms while monocots use tolerance mechanisms (Briske and Heitschmidt 1991).

Despite the advantage herbaceous monocots have over dicots, heavy grazing of grasses typically reduces spring growth rates and winter survival, shortens internode length, shifts upright leaves to a more prostrate form, reduces leaf width, and depletes carbohydrate reserves (Peterson 1962). Different grass species also respond differently to defoliation. Recovery of western wheatgrass after a single heavy defoliation required 14-26 months of rest, while blue grama plants required 2 years to make a fair recovery after three heavy defoliations (Trlica et al. 1977). Kentucky bluegrass stands lost vigor and experienced thinning when cut below 2.5 cm (Robinson et al 1952), but if clipped over 5 cm height over 3 years, did not lose vigor (Dovel 1996).

2.1.2 Defense Mechanisms

There are two main techniques that plants can employ to deal with defoliation. The first of these is avoidance. These mechanisms are defined as affecting plant accessibility and palatability. Accessibility of the plant will influence whether the animal is able to graze it. This is almost always a function of the proximity of plant tissue to the ground surface, which is determined by the length and angle of leaves and tillers, as well as the amount of dead material contained in the plant (Crawley 1983). The surface of the leaves can influence herbivore choice. Common surface defenses include an epidermis suffused with lignin, silica, cork or wax, which will make the leaf hard to bite or chew. The epidermis can also be defended by a covering of hairs (Pillemer and Tingey 1976; Rathcke and Poole 1975; Levin 1973), which makes it difficult to chew and swallow.

Palatability can include both mechanical and chemical defenses. Mechanical defenses include spines, awns, and epidermal characteristics (Young 1987; Cooper and Owen-Smith 1986; McNaughton et al. 1985). A thickening in cell walls decreases digestibility and causes the palatability of that plant to decrease (Akin and Burdick 1977), reducing herbivore preference. For example, prickles on *Rubus* plants exposed to cattle were longer and sharper than those on ungrazed individuals nearby (Abrahamson 1975).

Chemical defenses, known as secondary chemicals or metabolites, can also affect palatability. Qualitative compounds are low in concentration and are made at a low energetic cost to the plant, and are able to increase rapidly in concentration when needed. These include alkaloids, glucosinolates, or cyanogenic compounds (Rhoades 1979, 1985). Conversely, quantitative chemicals are energetically expensive to produce, present in large concentrations, and are easily detected by herbivores. These include tannins, lignins, and resins.

The second strategy by which a plant can defend against grazing is by tolerating it. This defense is primarily through accelerating growth rates after defoliation.

Compensation can occur in five ways: 1] reduced competition with other plants, 2] increased photosynthesis rates of the remaining leaf area, 3] mobilization of stored carbohydrate or protein reserves to form regrowth tissue, 4] altered photosynthate distribution patterns, and 5] reduced natural rate of mortality of plant parts (Crawley 1983). Studies show that defoliation can produce an increase in plant metabolism that is reflective of immune responses. This is associated with accelerated wound isolation, callus production, and the synthesis, transformation and redistribution of metabolites (Chew and Rodman 1979). The ability of a plant within a species to tolerate grazing is dependent on age, history of defoliation, carbohydrate and amino acid reserves, water status and a host of abiotic factors, like ice, fire, lightening, wind and pollution (Crawley 1983). If the plant is stressed by other factors, its ability to tolerate defoliation will be lower.

2.1.3 Photosynthesis and Carbohydrate Responses

Regrowth of tissue in grasses depends on carbohydrate reserves as well as amino acids, whereas leaf expansion in deciduous woody plants is entirely dependent on stored organic reserves (Crawley 1983). If patchy defoliation occurs on the plant, the undamaged part can spread photosynthate to the damaged part. However, frequent defoliation may result in the abandonment of the damaged part (Gutierrez et al. 1979; Wang et al. 1977). The primary reason that total net carbohydrate (TNC) reserves are monitored is because they provide a measure of leaf replacement potential (vigor), such that depletion of carbohydrate reserves by excessive defoliation reduces growth, or may even result in plant death (Weinmann 1948).

Grazing changes the age structure of leaves within the plant, and affects the rate of photosynthesis (Ps) expressed by those leaves (Fischer and Thomas 1989; Parsons et al. 1988). Defoliation that reduces the source increases the Ps rate (Khan et al. 2002). Flower, fruit, and root removal will reduce sink strength and depress Ps rates (Wareing et al. 1968; Maggs 1964). Plants generally experience maximum photosynthetic rates around the time of full leaf expansion (and decline thereafter) (Caldwell 1984), so defoliation can have a major influence on Ps capacity. The Ps ratio of fully expanded leaves decline as they age (Brown et al. 1966; Jewiss and Woledge 1967), due to increases in both stomatal and mesophyll resistances (Ludlow and Wilson 1971). This aging effect appears reversible if the plant is defoliated, probably due to stomatal opening in the remaining leaves (Gifford and Marshall 1973). However, if the amount of leaf area removed by grazing is so extensive that any increase in Ps rate is unable to compensate, the plant will be disadvantaged.

When defoliation does occur, maximum Ps rates do are not immediately experienced. This is because of the decreased Ps rates of older, non-defoliated leaves left by the herbivore. It takes several days for maximum rates to be reached (Dyer et al. 1982; Detling et al. 1979), which corresponds with the production of new (and highly Ps efficient) leaf tissue. After defoliation, the amount of photosynthate directed above-ground to replace lost tissue may be greater relative to the amount sent below-ground (Detling et al. 1979; Ryle and Powell 1975). This flexibility in allocation patterns seems to increase a species' tolerance to grazing.

2.1.4 Reproduction Responses

Defoliation has two main effects on the reproduction potential of a plant species. The first of these is a change in seed production. Size of seed can be reduced by plant defoliation as it causes a reduction in the plant tissue that supplies carbohydrates to seed sinks (Crawley 1983). Root feeding decreases fecundity by limiting the amount of water and nutrients the plant can take up, as well as causing reduced shoot growth, which as noted previously, depresses carbohydrate availability (Jones and Jones 1974). Above-ground defoliation not only indirectly affects reproduction by reducing Ps material, but can directly remove the reproductive structures via defloration or fruit predation. If there is not enough time left in the growing season for the plant to produce new fruiting structures, reproduction potential for that plant is lost (Crawley 1983).

2.1.5 Root Responses

Roots are essential to plant life, as they provide stability to the plant, and take up water, nutrients and gases. Root to shoot ratios normally remain uniform during vegetative growth, but naturally decline during flowering (Brouwer 1962), as carbohydrate is being directed from all areas of the plant to support reproductive structure development. Defoliation will alter this balance. A defoliated plant has more root to supply water and nutrients than the shoot requires. To re-establish equilibrium, the plant initiates new top-growth and allows respiring roots to die without replacement (Crossett et al. 1975) as carbohydrates are channeled from the roots to the shoot. A plant that is experiencing root defoliation is unable to support the demands of above-ground growth.

In order to initiate new root growth, old leaves are not replaced and existing leaves may senesce faster (Crossett et al. 1975) with carbohydrate now used for root growth.

The ability of a plant to recover after defoliation is dependent on the capacity for nutrient absorption per root length. Cessation of root growth will limit lateral and vertical development of roots (Smoliak et al. 1972; Schuster 1964), as well as diminish root initiation, diameter, branching, and overall root biomass (Richards 1984; Carman and Briske 1982; Evans 1973; Jameson 1963; Biswell and Weaver 1933). In many cases, root mortality results (Troughton 1981; Hodgkinson and Baas Becking 1977; Weaver and Zink 1946), reducing absorptive surfaces, and limiting the soil volume that can be explored for water and nutrients (Heitschmidt and Stuth 1991).

The amount of time root growth is suspended depends on how intense the defoliation regimes are. Any defoliation of grasses tends to depress root growth, respiration, and nutrient uptake within 24 hours (Davidson 1979; Troughton 1957). Defoliation that removed 80% and 90% of shoot biomass retarded root growth for 12 and 17 days, respectively (Davidson and Milthorpe 1966). The frequency of defoliation over a growing season will also affect how long root growth is suspended. An initial removal of 70% of above-ground biomass followed by three clippings per week suspended root growth for the duration of the experiment (33 days) (Hodgkinson and Baas-Becking 1977).

2.1.6 Mortality Responses

Any factor that decreases the ability of a plant to guard against defoliation causes an increase in death rate. Such things as pollination stress, water stress, root damage and drainage alteration will only augment the stress of tissue removal, increasing the potential for plant demise (Crawley 1983). A change in competitive ability seems to be the most common (and possibly the most important) result from tissue removal. Mueggler (1970, 1971) reported that the recovery of bluebunch wheatgrass [*Agropyron spicatum* (Pursh) Scribn. & Smith] and Idaho fescue (*Festuca idahoensis* Elmer) from heavy clipping is possible only if competition from surrounding vegetation is temporarily suppressed.

2.2 Competition Effects

Plants do not function as isolated individuals, but rather as members of a community. The competitive interactions are primarily modified through differential utilization of individuals and populations within a community as herbivores respond to avoidance mechanisms exhibited by different plant species (Briske and Heitschmidt 1991). Herbivores can influence the competitive relationship of plants in 4 ways: 1] a reversal in the relative competitive abilities of the plant species (if the preferred species is the most competitive plant, the least preferred plant becomes dominant), 2] a preference for the least competitive plant, which is now greatly disadvantaged and most likely eliminated from the community, 3] switching and feeding preferentially on whichever plant is the most abundant, and 4] entirely neutral in its effect, taking each plant species in proportion to it abundance (the outcome then depends on the relative grazing tolerances of the species) (Crawley 1983).

Primarily weed problems often occur in scenario one or two. Species that are preferred, and therefore grazed heavily, are more disadvantaged than those that are avoided, with the less stressed species experiencing a competitive advantage. These species are able to utilize the available resources and become bigger, which will reduce the amount of resources available to less competitive species. The luxury of having extra carbohydrate allows for enhanced root growth, which will increase access to soil water and nutrients (Eissenstat and Caldwell 1988; Mueggler 1972). Conversely, the reduced competitive ability of the dominant species can also increase diversity as it allows other less competitive, but more grazing tolerant species to enter the community (Crawley 1983).

Another mechanism by which competition is altered is through differing abilities among species to re-grow following similar defoliation patterns (tolerance mechanisms). Species that are better adapted to rapidly replacing lost Ps tissue will gain advantage over those that re-grow more slowly (Briske and Heitschmidt 1991). Therefore, those species that are grazed less severely and re-grow rapidly are going to have a high competitive fitness.

Although plant use rapid regrowth to recover from defoliation, the regrowth of previously defoliated tissue presents a tempting food source to herbivores. This typically results in repeated defoliation of a distinct area. Overgrazing occurs when animal productivity per unit area declines with more intense grazing. The short-term consequence is a reduction in productivity of the plant community. However, if overgrazing continues, species composition will alter to favor non-forage (often woody) plants species, or unpalatable weeds (Briske and Heitschmidt 1991). Continued defoliation can also cause drastic losses of plant material and cover, resulting in areas of erosion. Once this occurs, changes to the plant community may be permanent. In some cases, this will only result in a reduction in the amount of herbivory that can take place.

However, in most cases, once erosion begins to occur, animal needs cannot be met (Briske and Heitschmidt 1991). This severe type of patch development is what commonly leads to microclimate alterations, and subsequent deterioration in range condition.

Competitive interactions are evident when invader species enter a community. Many of the plants that have invaded the New World originated in the Mediterranean Basin and steppes of the Middle East (Heywood 1989). These regions have been subjected to a long history of human habitation and agricultural practices, and therefore have enhanced the traits that allow for invasion and competition (Masters and Sheley 2001). Often they are more fecund than native species, are more tolerant to resource constraints and can adapt to the altered chemical status of a site that is invaded (Masters and Sheley 2001). Despite the strong, invasive capabilities of these plants, the entry into an established community is dependent on the type and intensity of disturbance, propagule pressure (i.e. number of propagules and duration of community exposure to propagules), and the time interval between disturbance events (Blumenthal and Jordan 2000; Hobbs and Huenneke 1992; Rejmanek 1989). Grazing, soil disturbance, and soil fertility affect how well a community can defend against invasive weeds, and affects the entry ability and abundance of the weedy species (Edwards et al. 2000; Heimann and Cussans 1996; Ang et al. 1994; Thrasher et al. 1963; Bakker 1960). Therefore, the goal of management should be to improve degraded communities so they are less susceptible to invasion.

2.3 Grazing Systems

There are two fundamental management tactics that can be employed when designing a rotational livestock grazing system. These are: 1] high utilization grazing (HUG), and 2] high performance or high production grazing (HPG) (Booysen and Tainton 1978). The primary difference between these strategies is related to the way in which they affect the competitive interaction of the preferred (high grazing pressure or high GP) and non-preferred (low GP) species within a community. HUG strives to ensure that all plants are moderately to intensively defoliated during a given grazing period. HPG uses less intensive defoliation periods and therefore results in only preferred plants being grazed at light to moderate intensities. By forcing herbivores to consume non-preferred species, HUG tactics usually result in lower individual animal performance, but higher production per unit area than HPG strategies (Briske and Heitschmidt 1991). This occurs as animals, when given a choice in HPG, often defoliate higher quality material, resulting in greater weight gain. By choosing higher quality material, much biomass may be left behind, allowing these pastures to be re-grazed relatively soon thereafter, following a short rest period. With HPG, individual gain is maximized, while gain per unit area may be lower (especially if the site is made up of primarily low quality species).

Within the two main grazing strategies there exist many different grazing systems. Deferred and rest-rotation systems are multi-pasture, multi-herd or single herd systems designed to maintain or improve range condition utilizing HPG, HUG or other tactics. High intensity, low frequency (HILF) systems are multi-pasture systems usually stocked with a single herd. They are designed to maintain or improve range condition utilizing

HUG tactics. HILF attempts to reduce animal preference, preventing the over-utilization of a few preferred species. Short duration (SD) systems are similar to HILF systems except HPG rather the HUG tactics are employed to maintain or improve range condition (Briske and Heitschmidt 1991). Since intensity of defoliation is less in the SD systems than the HILF ones, grazers have more of an opportunity to select specific plants and plant material. Another grazing system that is commonly used is known as season-long or continuous grazing. This is a single pasture, single herd system that requires minimal management where the herd stays in one pasture for the entire grazing season. Animals have free choice to graze where they choose at all times.

The principal effect herbivores have on a plant species is not eating them to extinction, but rather through the modification of competitive abilities of one plant with another (Crawley 1983). Grazing management can be used to govern the intensity of competition by regulating the frequency and intensity of defoliation. Defoliation inherently alters competition through the removal of various tissues. Species composition is altered when a particular intensity, frequency, and/or seasonality of grazing shifts the competitive advantage from one group of species to another (Briske and Heitschmidt 1991).

Grazing intensity will affect the competitive interactions within a plant community. Moderate grazing may have little effect on species composition, even if species are not grazed uniformly or respond differently to defoliation, mainly due to the fact that defoliation is not intense enough to alter plant growth and survival. If severity of defoliation increases, differences in utilization and growth strategies among species begin to alter competitive interactions, and differences in composition begin to arise

(Briske and Heitschmidt 1991). When herbivore use is heavy on some areas and light (or non-existent) on others, as often observed in a continuous grazing strategy, plants in the heavily utilized areas will have trouble surviving but those in the relatively undisturbed area will flourish (Crawley 1983). Plants in these communities will alter their morphology so that most of the plant is ungrazable (close to the ground), which allows them to maintain enough tissue to recover from defoliation.

The season of grazing can also influence the way a plant responds to defoliation. The ability of a species to compensate for grazing depends on the progression of phenological development it goes through. Species that are continuously defoliated during their growth period, or defoliated early on in their development so potential growth is inhibited, will be less competitive that those who experience defoliation only at the end of their life or growth cycle (Briske and Heitschmidt 1991). For example, when pinegrass (*Calamagrostis rubescens* Buckl.) is grazed immediately after active growth and before the dry summer period, little regrowth will occur (Buwai and Trlica 1977; Stoddart and Smith 1955). Pinegrass is also susceptible to herbage removal during mid-summer when growth slows or stops (Stout et al. 1980). If grazed during these times, recovery is difficult.

Grazing systems can be used for weed control, either by directly defoliating weeds or damaging them, or indirectly by conditioning the pasture and making it more competitive against weeds (Popay and Field 1996). This type of control can improve pasture quality, reduce negative impacts on non-target species, return nutrients from herbivoires, and is relatively ‘environmentally friendly’. Using grazing management for weed control can be more sustainable, has lower direct costs, and the weeds that are defoliated can be converted to animal protein and thus, generate economic value. The costs associated with using grazing systems for control include animal purchase, fencing, and water systems. There is also the possibility of a loss of animal condition or value (wool or skin condition), uneven fertility, damage to the soil structure, and spread of weeds through seeds in the feces (Popay and Field 1996). Thus, each weed problem needs to be analyzed individually to find the best grazing system for weed control, pasture health and animal production.

2.4 Herbivore Choices

Many different factors affect how herbivores forage. Each herbivore type has a preferred habitat, which is defined by the plant species present, how they are spatially arranged, and their structural configuration (Stuth 1991). Habitat selection is modified by many levels of influence. The first level of selection occurs at the landscape level. Animals locate the boundaries of their landscape, what plant communities present, the seasonality of preferred species, and water location (Stuth 1991; Coleman et al. 1989), and make habitat choices based on these factors. There appears to be a hierarchy of needs that influences animal distribution. The greatest of these is thirst, followed by temperature regulation, hunger, nighttime protection from predators and finally a place for rest (Smith 1988). Optimum grazing area is defined by water placement, and sheep and cattle will usually not travel farther than 1.6 km from water for food unless necessary (Walker et al. 1987; Valentine 1947). Rough terrain, like steep slopes, rocky terrain or deep valleys restrict movement (Stuth 1991).

The next level of selection deals with the plant community level. Forage quantity and quality greatly influence where a herbivore chooses to graze, as does the seasonality of preferred species (Senft et al. 1985), which are always contained within the boundaries of the previous selection levels. Preferred grazing sites contain the bulk of the preferred forage of the grazing animal. Avoided sites are those containing low value food or are inaccessible by terrain. Limited occupation sites are those where high use occurs relative to the amount of forage available, such as along traveling paths (Stuth 1991). In any landscape where herbivores have a choice of what to feed on, patchy grazing will occur. This is because plant species are often distributed non-uniformly, and herbivore location will depend on their preference for certain patches.

Preferred and avoided grazing sites are dependent on the species of herbivore. Herbivores have a preference for primary food groups, and choose from either grasses, forbs or woody species (Provenza and Balph 1987). Bulk-feeders (e.g. cattle and bison) have high dry matter requirements, low nutrient requirements, unprehensile mouth-parts and a large rumen:body ratio (Demment and Van Soest 1981). Therefore, grasses are their primary food source because they have a high canopy bulk density. Conversely, intermediate feeders (e.g. goats and sheep) require greater nutrient content, less matter, and have prehensile mouth-parts, so they prefer smaller forbs that are higher in nutrient concentration than grasses (Stuth 1991). Many of the browse-preferring ungulates (e.g. deer and moose) have organs that allow them to select those plants where height, spineyness and secondary compounds would otherwise be restrictive (Cooper and Owen-Smith 1986).

Animals select plants in their diet primarily on the basis of nutrition. Quality of plants is determined by morphological, anatomical, phenological, and chemical characteristics (Huston and Pinchak 1991). These components can be altered by abiotic factors, such as air temperature and soil moisture. Commonly, grasses grown at high temperatures have lower digestibility and crude protein. Similarly, when soil moisture is restricted during vegetative growth, delayed maturation will maintain forage quality. However, if severe water stress occurs, quality decreases as carbohydrates are translocated and plant parts senesce (Huston and Pinchak 1991). Plant nutrients are used in order for animal maintenance, reproduction, lactation and storage (Huston and Pinchak 1991). Therefore, different ages, sexes and life-stages of animals will influence how they graze. Cattle forage intake decreases during late gestation and increases post partum when lactation requirements increase energy requirements (Weston 1982; Jordan et al. 1973). Body condition may affect intake, as abdominal fat is generally thought to restrict intake, while poor condition animals increase intake of high quality forage (Cowan et al. 1990; Fox 1987; Freer 1981). Different genetics within a species exhibit different forage requirements. For example, Simmental cows displayed greater intake requirements than Hereford cattle in free-ranging conditions (Havstad and Doornbos 1987). Dairy cattle breeds are also known to have higher maintenance requirements than beef breeds (Soils et al. 1988). Temperature stress will also affect intake rates. When animals are under cold stress, intake will increase. Conversely, when encountering heat stress, intake decreases (Huston and Pinchak 1991).

2.5 Canada Thistle [*Cirsium arvense* (L.) Scop.]

2.5.1 Taxonomy

Canada thistle (CT), a member of the Asteraceae family, is known by many names, including creeping thistle, California thistle (Meadly 1957) and appropriately, "cursed thistle" (Stevens 1846). CT's latin classification has varied over the years. In 1687, Tabernaemontanus named it *Carduus arvensis*; Tournedfort changed it to *Cirsium arvense* in 1700; Linne altered it to *Serratula arvensis* in 1753; Scopoli changed it back to *Cirsium arvense* in 1772; Robson returned to *Carduus arvensis* in 1777; while Hoffman renamed it as *Cnicus arvensis* in 1804 (Detmers 1927). Currently, CT is referred to as *Cirsium arvense* (L.) Scop. (Fernald 1951; Stevens 1950). Regardless of these multiple name changes, the number of chromosomes in the *Cirsium* genus is always n=17 (Aishima 1934).

Much of the confusion in naming this species may have resulted from the high level of variation existing within *Cirsium arvense* populations. Morphologically different ecotypes were discovered as early as 1939 (Spence and Hulbert 1935). Ecotypes were defined by Lawrence (1955) as "a subdivision of a species having its own distribution but not sufficiently distinct (morphologically or genetically) to deserve elevation to the rank of species", while Odum (1971) defined them as locally-adapted populations of a species with a wide geographic range. Four ecotypes of CT are commonly acknowledged (var. *vestitum* Wimm. & Grab., var. *integrifolium* Wimm. & Grab., var. *arvense* and var. *horridum* Wimm. & Grab.). The variety *horridum* is the most common and is found across Canada. Other ecotypes are localized in various provinces, with var. *integrifolium* and var. *horridum* the only ones documented in Alberta (Moore 1975).

2.5.2 Description

Many descriptions of CT and its' life cycle have been written, reflecting the prominence of Canada thistle around the world (Holm et al. 1977; Hodgson 1968; Hamdoun 1967; Bakker 1960; Hayden 1934; Detmers 1927). Moore (1975) studied CT in Canada and provided a biological description of the plant. Most notably, this perennial plant actively spreads by creeping roots, which can extend from 1.25 to 12.2 $m \cdot yr^{-1}$ in Europe and North America (Chancellor 1970). Creeping roots then produce many aerial shoots, with stems that are slender, green in color, branched and can range from 30 to 150 cm in height. The alternate leaves have a sessile base that is clasping or shortly decurrent, and oblong in shape. Leaves are either entire or deeply pinnate, and can vary in abundance and type of spines, with short, fine spines or long, prominent spines. Leaf texture varies, with the upper surface being glabrous, and the underside glabrous, lightly arachnoid or tomentose. Stems are terminated by numerous dioecious flower heads, anywhere from 1-5 heads per branch. Heads are 15-25 mm high and $^1/_4$ to $^1/_3$ as wide, consisting of only tubular florets that are rose-purple to pinkish, and less commonly white. Male heads are globular in shape, while female are flask-shaped and somewhat larger (23-26 mm) than the male heads (12-14 mm). Seeds range in size from 2.5-4 mm by 1 mm, have copious, white, feathery pappus, and are straw or light brown in color (Moore 1975).

Ecotypes of CT vary morphologically in leaf texture, margin outline, photoperiodism, stomatal frequency, leaf cuticle waxes, relative leaf weight, seed dormancy, germination and spininess (Moore 1975; Hunter and Smith 1972). They also have differences in vigor, growth habit (Moore 1975; Hunter and Smith 1972) and response to control practices like tillage and herbicides (Donald 1990; Hodgson 1970; Smith et al. 1968; Bakker 1960). The stage of development that is most susceptible to herbicide can differ between treatment and ecotype (Hodgson 1970).

2.5.3 Root Growth

The strong perenniation of CT comes from the root system, which can survive indefinitely (Moore 1975). While aerial shoots are terminated each year by the commencement of frost, root carbohydrate storage allows the root system to survive winter (Moore 1975). Rogers (1929) described root activity over these cold months. Shoots grew from root buds as long as the ground was warm. When soil froze (middle of November), shoots died and no new shoots were formed throughout December (when ground was frozen to a depth of 50 cm). In early January, buds on larger roots increased in size, and by the middle of January, had developed into thick, vigorous, pointed underground shoots that range in length from 15-20 mm and 3-5 mm in diameter. By February, new horizontal roots formed on old roots, and shoot length increased to 4-7 cm. Rogers (1929) also found more buds were produced on the "kinks" of horizontal roots. At the beginning of March, new horizontal roots were 15-30 cm long and 2 mm in diameter, and when the soil was no longer frozen, development of the whole root system accelerated. Hodgson (1968) showed that emergence of shoots began when mean weekly temperatures were 5°C, and was optimized at 8°C in Montana, corresponding to early

May. Rosette development and rapid vertical growth occurred approximately 3 weeks after emergence. Growth of 3 cm per day, the most rapid growth rate, occurred between mid and late June, while growth decreased to near zero in July and early August. Nadeau and Vanden Born (1989) reported CT stands with mean density of 40 shoots·m^{-2}, though densities can exceed 60 plants·m^{-2} on areas of farmland in North America (Donald 1990). Generally, maximum CT growth occurs when air temperatures range from 15 to 25°C (Alberta Agriculture, Food, and Rural Development 1984).

2.5.4 Vegetative Reproduction

In CT, adventitious root buds and root mass are largely responsible for both vegetative propagation of shoots from roots and persistence of established patches (Donald 1990). Seedlings begin with development of a fibrous tap-root that after a few months produces lateral roots that spread horizontally. After horizontal roots reach 6-12 cm in length, the root bends downward toward the water table. A new horizontal root commonly develops at this bend, which continues the horizontal spread of the root system. Buds on the original vertical root or arching branches of the horizontal roots can produce aerial shoots (Donald 1990; Magnusson et al. 1987; Sutton and Tinus 1983; Moore 1975). The rate of root expansion of young plants was estimated at about 1 cm·day^{-1} (Nadeau 1988), and horizontal roots can extend from 1.25-12.2 m in one season (Chancellor 1970; Bakker 1960; Hayden 1934; Rogers 1928). CT roots are generally concentrated at a depth between 20 and 40 cm. Despite this, vertical roots often penetrate to the water table (Hayden 1934) and depths of 2-3 m are common (Nadeau and Vanden Born 1989; Hunter 1985; Pavlychenko 1943). Malzev (1931) reported penetration depths of 5.5 m in Russia, and Rogers (1928) found vertical roots to a depth of 6.75 m.

Very small pieces of CT root are capable of reproducing. Root fragments as small as 6-8 mm can produce shoots (Prentiss 1989; Forsberg 1962) and segments 6 cm long can produce 1+ shoots in as little as 5 days (Sagar and Rawson 1964). Magnusson et al. (1987) reported that under favorable conditions, root systems that develop from both aerial and subterranean stem sections can overwinter and produce infestations the following year. When roots were cut to 10 cm and planted, the root system that developed produced an average of 930 shoots and over 111 m of root length larger than 0.5 mm in diameter (Nadeau and Vanden Born 1989).

Vegetative bud growth enables the perenniation of CT. Root buds were more abundant in the top 20 cm of soil, while buds produced on roots below 40 cm of soil often did not produce shoots when replanted (Nadeau and Vanden Born 1989). The average number of buds detected on roots ranged from 1.0 to 2.6 buds$\cdot$10 cm^{-1} of linear root. Root bud growth was greater in the winter (1.5 to 2 cm root bud length$\cdot$cm root length^{-1}) than in the summer (0.3 to 0.8 cm root bud length$\cdot$cm root length^{-1}) (McAllister and Haderlie 1985). While aboveground shoot density may not change between years, underground bud development does not stop and can range from 1.4-2.6 times the amount of shoot production per year (Nadeau and Vanden Born 1989).

CT is a fructan-storing plant (Ozer and Koch 1977), which has been implicated in physiological functions such as cold hardiness and phloem transport (Nelson and Spollen 1987). Total non-structural carbohydrate (TNC) levels in CT root tissue were lowest in spring due to active shoot growth following winter. These reserves were not replenished during summer while active shoot growth occurred, and it was not until fall (i.e. throughout September) that carbohydrate levels began to increase in the roots (McAllister and Haderlie 1985; Hodgson 1968; Sagar and Rawson 1964; Bakker 1960; Arny 1932; Welton et al. 1929). Competition for water (Hunter and Smith 1972) and available N (McIntyre 1972) are important factors that regulate the inhibition of root bud elongation (McAllister and Haderlie 1985).

Dormancy of buds is another mechanism used by CT to enhance longevity (Tworkoski and Sterrett 1987; Hoefer 1981; McIntyre and Hunter 1975; Carson 1974; Hamdoun 1970). Freezing of buds reduced both survival and vigor (i.e. dry weight of emerged shoots), although vigor is generally reduced by temperatures warmer than those affecting survival. While CT roots can survive and even appear metabolic over winter (see above), CT root buds seem to undergo little hardening, and temperatures of –6°C for 8 hours killed root buds and severely injured them at –2°C, although this is highly dependant on the depth at which the overwintering buds were located (Schimming and Messersmith 1988).

Shoot density is often a good indication of root growth. Shoot production recorded in early June or late July has been shown to be a positive linear function of density measured in late July of the previous year, or of fresh root weight or adventitious root bud density measured in early September the year before (Donald 1993). Both shoot density and root variables measured in late summer were equally accurate in estimating shoot density the following spring, and shoot density measured in late summer estimated shoot density the following summer more accurately than either adventitious root buds or fresh root weight.

2.5.5 Floral Reproduction

While CT relies primarily on vegetative reproduction (Donald 1994; Friedli and Bacher 1991; Donald 1990), it can also reproduce from seeds. CT is a long-day plant, which flowers profusely with 18 hours of light, but does not flower with less than 12 hours of light (Link and Kommedahl 1958). While seedlings die when light intensity is less than 20%, growth is restricted in light less than 60-70% of full daylight (Bakker 1960). CT as a whole is neither gynodioecious (both male and female contained in one flower) nor dioecious (Correns 1916), and can have populations with either pure females, almost pure with some hermaphrodite males, purely dioecious (Bakker 1960), or clearly gynodioecious (Correns 1916). However, most often CT plants are dioecious (Lloyd and Myall 1976; Moore 1975). CT plants are obligate outcrossers, relying on insects, (specifically honeybees) for pollination (Moore 1975; Derscheid and Schultz 1960). While average seed production is 1530 seeds/plant, one plant may produce up to 5300 seeds (Hay 1937), with viable seed produced 8-10 days after flowering (Moore 1975). The number of seeds developed is highly dependent on the distance between male and female plants. Seed numbers are greater when male and female plants are within 33 m, but when separated 160 m, only 2-3 seeds form per head (Hayden 1934). Limited seed can still be formed when plants of either sex are separated up to 390 m (Amor and Harris 1974). Finally, variation in seed set is influenced by genetics (Mazer 1987a,b; Cavers and Steel 1984; Thompson 1981), microclimatic (Wulff 1986), and herbivore effects (Crawley and Nachapong 1985; Hendrix 1979).

Because CT seeds have a plumose achene, they are well-adapted to wind dispersal (Blumenthal and Jordan, 2000; Jewett et al. 1996), and maximum dispersal has been estimated at 11.4 m (Sheldon and Burrows 1973). However, dispersal distance is limited by the tendency for the pappus to break off (Bostock and Benton 1979; Bakker 1960), and Bakker (1960) found that only 9.9% of pappus collected 10 m from parent plants were still attached to an achene. CT seeds also contain elaiosomes (lipid-rich, fleshy appendages) (Pemberton and Irving 1990), which attracts ants, and in turn promotes seed dispersal (Bresinsky 1963; Ridley 1930; Sernander 1906), enabling exotic plants to invade natural vegetation (Pemberton and Irving 1990). Long distance seed dispersal by water, including irrigation water, also facilitates CT spread (Moore 1975).

The majority of research conducted on CT seed germination reports that no scarification is required (Moore 1975). However, CT seeds are capable of exhibiting dormancy, or arrested growth and development, until germination requirements are fulfilled (Baker 1974), which enables them to escape control by chemical, cultural, mechanical and biological means (Foley 2002). Flowers must be open for a week or more before achenes are mature enough to germinate (Derscheid and Schultz 1960). Germination can begin at air temperatures of 15-20°C and high light intensities, but are greatest at air temperatures of 25-30°C (Bakker 1960; Moore 1975). Seed collected from Australia stored at 20°C for 6 months had an average germination of 78% (Amor and Harris 1974). Freshly gathered seed has been reported to have a germination rate as high as 95% (Hayden 1934), but more commonly had a germination rate of 50-80% (Hodgson 1964). Germination rates from a variety of studies are as follows: 42-66% after dry storage at room temperature (Derscheid and Schultz 1960); 62% after dry storage for 8 months, 25% after dry storage for 12 months, and 38-71% after dry storage for 2 years (Hayden 1934). When submerged in water for 6 months, 70% of seeds germinated

(Bruns and Rasmussen 1957). Seeds retrieved after 6 years of burial had 26% germination, dropping to 5% after 21 years, with no viability after 30 years (Toole and Brown 1946). However, Derscheid and Schultz (1960) reported no correlation between seed age and germination rate.

Germination varies with ecotype (Hodgson 1964) and stored seed-bank depth in the soil, with greater germination from the seeds retrieved from the deepest soil (Toole and Brown 1946). Cloddiness of the soil also affects germination rates, as more cloddy soils restrict oxygen levels and have high moisture levels, promoting seed dormancy (Terpstra 1986).

2.5.6 Habitat and Distribution

Canada thistle is considered one of the worst weeds around the world (Holm et al. 1977), causing large economic losses on a global scale despite eradication efforts (Peschken et al. 1982; Schröder 1980). While the exact center of origin is not know for this weed, it is thought to be native to southeast Europe and the eastern Mediterranean (Moore 1975). CT is the third most important weed in Europe (Schröder et al. 1993), the most troublesome of all thistles in Canada (Maw 1976), and a serious problem in the north central region of the United States (Doll 1984). CT is also endemic to Asia Minor, across central Asia to Japan, and extends to 30°N latitude in northern Africa and Afghanistan (Holm et al. 1979; Holm et al. 1977; Moore 1975). It is present in the temperate zones of South Africa, Africa, New Zealand, and Australia (Holm et al. 1977; Moore 1975). In Europe, the weed extends to Scandinavia (68°N), and exists in Siberia but does not flower north of 58°N latitude (Kolokolinkov 1931). The range of CT extends across nearly 10 million km^2 in North America, from 2090 km north to south and 4700 km east to west (Moore 1975). CT is found as far north as 59° latitude in Canada and as far south as 40° latitude in the US (Erickson 1983). In Minnesota, CT was found in 65-75% of all Conservation reserve program (CRP) fields statewide, and had a mean groundcover of 2.0-2.7% (Jewett et al. 1996). In Canada, CT extends across the country with populations increasing from West to East, from 39.3 to 83.1% (Moore 1975).

Canada thistle was a troublesome weed in Europe as early as the 16th century (Dewey 1901). CT arrived in Canada from Europe (Donald 1990), probably in the 17th century (Moore 1975), and spread to Vermont and New York (Stevens 1846). However, Hansen (1918) believes the weed was probably independently brought in as a contaminant in farm seed in both New France and New England. As early as 1795, Vermont instituted a law to halt the spread of CT. In 1844, Ohio enacted a law to limit the sale of CT contaminated seed, and landowners had to mow infested land and roadsides (Detmers 1927). Canada included CT as a noxious weed in the Federal Seeds Act in 1937. Across the western prairies, CT was listed as a noxious weed between 1960 and 1970, the latter of which included Alberta. In Alberta, it has been estimated that as many as four million ha are infested with CT. This appears to be increasing, with 35% of cereal and oilseed fields having thistle from 1987 to 1989 increasing to 53% of fields in 1997 (Thomas et al. 1998). Although most of the surveys conducted are on cultivated land, Moyer et al. (1991) reported that 90% of irrigated alfalfa seed fields in southern Alberta have CT. Other surveys of the Peace River Region in British Columbia (Thomas and Wise 1983), and Manitoba (Goodwin et al. 1986) state that CT is as much a problem in forages as in annual crops.

Due to the adaptability of CT, this plant is common in nearly all types of plant communities, including cultivated land, natural rangeland, pastures, hay fields, lawns, gardens, roadsides, railways allowances, and in waste areas (Frankton and Mulligan 1987; Moore 1975). CT prefers areas with moderate temperatures in the summer (10-32°C) and rainfall of 400-900 mm·year^{-1}. Growth is promoted by well-aerated soils, and low soil oxygen levels or a high water table can cause growth restrictions (Hodgson 1968). Despite this, CT can exist along water-logged areas, like streambanks, wetland edges, and lakeshores, but are restricted to where soil is not saturated. CT plants have been found in a wide range of soils in Canada, including clay loam, sandy loam, sandy clay, silt loam, and sand (Moore 1975; Hodgson 1968). Canada thistle will tolerate some salinity, and has been found on soils with salinity of 2% (Donald 1990), and found in 40% of nonmarsh, dry saline sites in Alberta (Braidek et al. 1984). CT is sensitive to low light intensity, and if they experience excessive amounts of shade, stems become tall and weak, where flower and seed production are limited (Moore 1975).

The presence of CT in many environments is likely due to its adaptability. Many studies report CT has the ability to exhibit great plasticity in order to survive (Schlichting 1986). This is exemplified in its response to moisture stress. While moderately stressed and unstressed plants appeared unaffected by water stress, severely stressed plants were wilted, with some necrosis around the margins of lower leaves (Lauridson et al. 1983). Shoot production was inhibited at 20% or less of field capacity (Dizenfog 1958). However, reduced soil moisture increased root length in the 0 to 30 cm soil horizon (Lauridson et al. 1983) and creeping roots remained viable even when dried to 20% of their original moisture (Forsburg 1962). This increases the difficulty for control because of the greater root length and high viability when plants are exposed to prolonged moisture stress (Lauridson et al. 1983). Conversely, CT is able to inhibit root bud initiation under moisture stress, and when moisture levels then rise (RH from 50 to 90%), stem height and shoot dry weights increase by more than 50%, while dry root weight increases 80% (Hunter et al. 1985). This allows CT plants to lay dormant until better conditions arrive, at which point abundant growth is expressed. Root fragments were still able to produce either roots or shoots when soil moisture was low, but not both at the same time (Hunter et al. 1985). Conversely, water logging for short periods (2 days) did not affect the production of shoots from fragmented roots, but as this time period increased, shoot production decreased, and with 12 days or longer, the final number of shoots produced by the root significantly decreased (Hunter et al. 1985).

2.6 Control Methods

Many control methods for CT have been described, and are classified in the general categories of chemical, cultural/mechanical and biological control. Specific control measures include cultivation, mowing, burning, competitive crop competition, smothering, herbicides, grazing and biological control agents (Donald 1990). Despite weed control efforts over the last century, the abundance of major agricultural weeds has steadily increased (Crawley 1987; Forcella and Harvey 1983) and weed invasion has not stopped (Ghersa and Roush 1993). This fact, combined with the rapid growth and longevity of CT, suggests that one treatment method, regardless of it's effectiveness, is unlikely to remove the weed from an infected area (Masters and Sheley 2001; Liebman and Gallandt 1997; Jordan 1996; Ang et al. 1994; Swanton and Weise 1991; Strand 1982; Trumble and Kok 1982; Lee 1952). Using combinations of control methods is known as integrated weed (or pest) management (IPM), and while individually each control method is incomplete, together they can cause the weed population to rapidly decrease (Hoeft et al. 2001; Jordan 1996; Pester et al. 1996). IPM focuses on managing ecosystem function (energy flow and nutrient cycling) so that open niches are not created after weed control, and preventing the entry of new invasive species (Masters and Sheley 2001; Masters et al. 1996; Sheley et al. 1996; Scifres 1986). IPM also implements successive years of control, rather than a one-time, intensive control effort (Masters and Sheley 2001; Ang et al. 1994; Donald 1990), which can reduce the environmental impact of the treatments (Zimdahl 1999; Ang et al. 1994; Apple and Smith 1976). In addition, there is often a cost benefit to using IPM, whereas non-IPM strategies often use more chemicals or fertilizer (Sreenivasulu et al. 2002; Balappa-Shivaraya 1999).

2.6.1 Chemical Control

The primary control method currently used for CT is herbicides (Bovey 1995). Extensive research has been conducted on the effectiveness of herbicide control, as well as how much and when to apply chemicals on both annual crops and perennial forages (Donald 1990). Research reviewed in Donald (1990) has shown CT is most susceptible to herbicides when carbohydrate levels are low in the roots, which coincides with the bud stage, occurring in early summer. Selective broad-leaf herbicides that are effective for CT control include 2,4-D (2,4-dichlorophenoxy acetic acid), dicamba (3,6-dichloro-2-methoxybenzoic acid), picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid), and clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) (Grekul 2003; Donald 1990). Dicamba and 2,4-D move through the leaves and shoots of CT, which provides mainly above-ground control, whereas picloram and clopyralid move through the above-ground and below-ground plant material, providing longer-term control (Turnbull and Stephenson 1985; O'Sullivan and Kossatz 1982; Hunter and Smith 1972; Chang and Vanden Born 1968, 1971). Both picloram, and to a lesser extent clopyralid, have persistence in soil, and are able to enter and move through the plant rapidly, causing severe damage to roots (Turnbull and Stephenson 1985; O'Sullivan and Kossatz 1984; Sharma et al. 1971; Vanden Born 1969). Although 2,4-D is effective in controlling CT shoots, repeated applications in a year, or across multiple years (3-5) are required to reduce thistle densities (Amor and Harris 1977; Gallagher and Vanden Born 1976; Schreiber 1967; Hay and Ouellette 1959).

Herbicides have the ability to increase grass production in pastures. When 2,4-D, clopyralid and picloram were used individually, they increased grass production by 110, 314 and 212% over 3 years, respectively (Reece and Wilson 1983). However, many of these herbicides remove legumes from pastures as well as CT. Picloram+2,4-D eliminated white clover (*Trifolium repens* L.) from the sward (Amor and Harris 1977), picloram removed red clover (*Trifolium pratense*) (Peterson and Parochetti 1978), and dicamba reduced red clover by 57-87% (Peterson and Parochetti 1978). This problem may be reduced by selective application, either via spot-spraying (Alberta Agriculture, Food, and Rural Development 2003) or wiper applications (Moomaw and Martin 1990; Boerboom and Wyse 1988; Wyse and Habstritt 1977).

Repeated application of herbicides can negatively impact an area. For example, there is potential for surface water contamination that can adversely effect desirable plants (Masters and Sheley 2001). There are also areas where applying herbicide control is difficult, or not allowed by regulation. Herbicide control is the main control method used in conservation tillage systems (i.e. minimum or zero till) because mechanical control is no longer an option. Because of this, weed species composition may change to intractable species or those with herbicide resistance (Hoeft et al. 2001; Coffman and Frank 1991; Buhler and Oplinger 1990).

2.6.2 Cultivation

Tillage has long been used to control CT in annual crops (Hodgson 1955, 1968, 1970; Derscheid et al. 1961; Detmers 1927). Cultivation mechanically damages shoots and leaves of the plants, as well as causes root damage, reducing root carbohydrate reserves. New shoot emergence is also inhibited, and can help reduce carbohydrate supply (Hodgson 1968). This type of control tries to eradicate CT by destroying top growth to starve roots (Donald 1990; Hodgson 1968). With some exceptions, cultivation has been generally successful at reducing CT densities, especially in regions with higher rainfall (Zimdahl and Foster 1993; Carlson and Donald 1988; Alley 1981; Arnold and O'Neal 1972). Notably, some ecotypes can withstand more disturbance, and therefore respond differently to cultivation (Hodgson 1970). However, cultivation may increase the potential for soil erosion, is unable to reach deep roots, can be very costly, and may spread small fragments of roots, increasing weed distribution (Donald 1990; Tustian and Raper 1980; Willard and Lewis 1939).

2.6.3 Fertilization

Fertilization has the potential of either reducing or expanding CT populations, by altering interspecific competition (Donald 1990). The density of CT in stands that received supplemental N was as much as 200% greater than those that did not, and fertilized CT also had greater shoot dry weight, greater root growth and greater root dry weight, as well a greater percentage of emerged buds from roots (Grekul 2003; Nadeau and Vanden Born 1990; McIntyre and Hunter 1975; Hamdoun 1970; Thrasher et al. 1963). Donald (1990) and Reece and Wilson (1983) reported CT densities increased with broadcast N application, although when crops were irrigated, CT was reduced, especially at high N levels. Apparently, irrigation and high N fertilization favored forage growth, which allowed them to interfere with CT growth (Bourdôt 1996; Donald 1990; Thrasher et al. 1963). While fertilizer addition may not increase plant density, plant biomass can increase, so that there are fewer, bigger, more vigorous plants (Grekul 2003). This can shift the competitive relationships towards the bigger CT plants. Conversely, when paired with other control methods, fertilization often increased the reduction of CT. When 2,4-D was sprayed in wheat, CT control was greater when nitrogen was added (Hume 1982; McKay et al. 1959). Grekul (2003) found similar reductions in CT densities in permanent pasture when CT was controlled using herbicides. CT response to fertilization is inconsistent for many reasons: initial soil nitrogen levels are variable, different forms on N may affect the plant differently (Reece and Wilson 1983), water can contain various levels of N, and climate can alter plant response (Reece and Wilson 1983;

Hume 1982; Hodgson 1958). Finally, phosphorous fertilization has been shown to increase CT densities (Edwards 2000).

2.6.4 Mowing

Mowing, which is a form of direct defoliation of plant material, can be used to control CT. Mowing is often used on rangeland to control noxious annuals and perennials (Benefield et al. 1999; Tyser and Key 1988). While the underlying physiological or biochemical mechanisms as to why mowing can control CT have not been examined, several studies have shown the benefits of mowing. Mowing can prevent seed production, reduce carbohydrate reserves, and cause a competitive shift towards desirable perennial grasses (DiTomaso 2000; Welton et al. 1929; Detmers 1927). Frequent mowing during the growing season can substantially reduce CT populations in forage stands (Wilson and Kachman 1999; Hartley and James 1979; Amor and Harris 1977; Hodgson 1958,1968; Schreiber 1967; Thrasher et al. 1963; Derscheid et al. 1961; McKay et al. 1959; Welton et al. 1929; Detmers 1927), and 3 years of mowing treatments severely reduced CT in most studies. Some studies report frequent mowing only weakened thistle (Foote et al. 1970; Willard et al. 1939), but these did not report start dates, mowing height, frequency or duration (years of treatment). It is important to note that that two or three years of multiple mowing treatments seem to be required for effective control (Schreiber 1967; Hodgson 1958; Welton et al. 1929).

The timing of mowing appears important to the success of CT control. Mowing seems most effective when begun in June and repeated at monthly intervals. Unfortunately, such frequent mowing intervals are likely to limit forage production.

Few, if any, researchers have looked at the long-term effect of mowing on CT infestation, so that re-infestation and longevity of control is unknown. Mowing combined with other control methods may prove to be the most effective solution. Combined with mowing, seeding competitive perennial forages suppressed CT infestations (Thrasher et al. 1963; Derscheid et al. 1961; Hodgson 1958). Mowing combined with chemical control also reduced CT populations. Wilson and Kachman (1999) used a single clopyralid treatment and two mowings to successfully reduce thistle populations. While mowing appears to control thistle, infrequent mowing provides ineffective weed control (Amor and Harris 1977), and in some cases, increases CT density if only mowed once in the growing season (Grekul 2003).

2.6.5 Biological Control

Biological weed control has been used against invading species threatening ecosystems, habitats and desirable species with some success, and has been described by Müller-Schärer et al. (2000). However, the ability of biological agents to control CT has had limited success (DiTomaso 2000; Donald 1990; Trumble and Kok 1982). High levels of genetic diversity in the target species, limited compatibility of agents with the target plant, and predation or parasitism of biocontrol agents are often the reasons success is not observed (Sheppard 1992). Additionally, many biological agents introduced to control CT also attack native thistle species, which reduces both their effectiveness (Louda et al. 1997; Turner et al. 1987; Goeden and Ricker 1986, 1987) and the willingness of regulators to allow their use. However, there is some promise of finding a biological agent for CT. In the absence of effective root feeders, a complex of leaf and shoot feeding species appears to have the most destructive potential (Schröder 1980). Eighty-four species are believed to damage CT (Moore 1975).

Several insects from continental Europe have been studied for biological control of CT in Canada. *Altica carduorum* Guer. (flea beetle) was found by Harris (1964) to eat the leaves. This insect was released in Ontario, Nova Scotia, Alberta and B.C. during 1963-68 but does not seem to have become well-established (Peschken 1971). The beetle was released again in Ontario in 1970 (Williamson 1971). It has been released in some US states and in Great Britian as well, but still hasn't been successful in reducing CT populations. Adults of *Ceutorhynchus litura* (F.) eat young thistle shoots but do not cause serious damage. The weevil was released annually near Belleville, Ontario from 1965-1967 (Peschken and Beecher 1973; Peschken 1971) and at Indian Head, SK in 1973 (Williamson 1974). A colony became established at one of four sites in Ontario, and in a 400 m^2 area the number of CT shoots decreased to 4% of the original density between 1968 and 1972 (Peschken and Beecher 1973). *Urophora cardui* L. seems to be a promising control agent but has yet to be released (Moore 1975). *Ceutorhynchus litura*, which is a European stem-mining weevil, is able to reduce the production of new shoots from overwintered buds on the roots, and may reduce vegetative spread (McClay 1993).

Mycoherbicides, sprays formed from diseases to control CT, have shown more success than most insect biocontrol research. *Alternaria cirsinoxia* condia has been used as a bioherbicide, and while it causes severe infection in older, basal leaves, the plant can escape by growing young leaves (Green and Bailey 2000). *Pseudomonas syringae* pv. *tagetis* was able to cause apical chlorosis and reduce seed production, but was not able to kill the plant (Johnson et al. 1996; Gronwold et al. 2002). *Sclerotinia sclerotiorum* showed potential of suppressing CT as well (Bourdôt et al. 2000, 2001).

Insect defoliation combined with planting of competitive forage species seems to reduce CT populations. Ang et al. (1994, 1995) showed that the use of *Cassida rubiginosa*, which defoliates CT, along with planting competitive species like tall fescue (*Festuca arundinaceae* Schreb.) and crownvetch (*Coronilla varia* L.), were able to reduce CT biomass. Added stress to the weed allowed the desirable vegetation to compete, and over time, replace CT in the stand. The use of two biological agents can also increase the likelihood of weed suppression. For example, *Apion onopordi* Kirby, a shoot-base boring weevil, and *Puccinia punctiformis* (Str.) Röhl, a rust fungus, are both parasites of CT. Examining their individual biology has been the primary focus of studies (Bacher et al. 2002; Friedli and Bacher 2001), but there is also potential for using both species simultaneously to control the weed.

2.6.6 Competition

Plant competition from aggressive species may serve to facilitate control of CT. Because CT is susceptible to shading, its growth can be reduced by species that restrict light availability (Jordan 1996; Pester et al. 1996; Donald 1990; Pook 1983; Medd and Lovett 1978). Perennial grasses are generally competitive, and 2-3 years after establishment, Wilson and Kachman (1999) found that perennial grasses were just as effective as clopyralid and two mowings each year for controlling CT. Tall fescue has been reported to reduce CT density by 60-78% (Kachman 1999; Ang et al. 1994; Reece and Wilson 1983; Thrasher et al. 1963). Kok et al. (1986) reported similar findings with tall fescue and musk thistle [*Carduus nutans* (L.)]. Hybrid wheatgrass, derived from a cross of bluebunch wheatgrass [*Agropyron spicatum* (Pursh.) Scrib. and Smith] with quackgrass [*Elytrigia repens* (L.) Neuski.], has been found to reduce CT density by an average of 85% over 3 years (Wilson and Kachman 1999). Thick stands of native switchgrass (*Panicum virgatum* L.) were able to reduce CT invasion (Jewett et al. 1996), and seeding smooth brome (*Bromus inermis* Leyss.) and mowing for three years suppressed CT by 90% (Derscheid et al. 1961). Dense plots of alfalfa (*Medicago sativa* L.) were reported to reduce CT densities from 33 to 11 plants$\cdot$m^{-2} (Schreiber 1967), and seemed better than grasses at controlling CT (Detmers 1927). This may be attributed to rapid canopy closure early in spring (Spence and Hulbert 1935; Rogers 1928; Detmers 1927), and an ability to withstand early and multiple mowings, which serves to suppress the weed (Donald 1990).

2.6.7 Grazing

While many scientists acknowledge that weeds can enter an area because of livestock selection and overgrazing (DiTomaso 2000; Hobbs 2000; Sutherst 2000; Hobbs and Huenneke 1992; Callihan and Evans 1991; Hobbs 1991; Hobbs 1989; Mack 1989; Reece and Wilson 1983), managed grazing can control weeds (DiTomaso 2000; Sheley et al. 1998). Rotational grazing can reduced weed spread, while continuous grazing allows for rapid weed spread (Hartley 1983; Trumble and Kok 1982; Bendall 1973; Feldman et al. 1968). The ability of a grazing system to alter vegetation growth patterns depends on the exact grazing regime, the season or time of grazing, and defoliation intensity (Bullock et al. 2001). Timing is essential, and should be conducted when the weed species is most susceptible to defoliation, and when impact is minimal on desirable vegetation (Kennett et al. 1992). Animals can remove young shoots or seedlings from CT or consume seeds and flower heads (Mitchell and Abernethy 1993; Amor and Harris 1975). In order for animals to be used, they must be available for use, and able to be fenced onto or off an area (Popay and Field 1996). For many years, goats and sheep have been recommended for CT control in pastures (Popay and Field 1996; Donald 1990). In Australia, heavy grazing by sheep reduced CT spread (Amor and Harris 1975). Goats are also able to control thistles, and can be grazed with cattle without affecting the productivity of either species (Popay and Field 1996; Thomson and Power 1993). Cattle were able to provide some control of yellow star thistle (*Centaurea solstitialis* L.) (Thomsen et al. 1993). Cattle also seem to push into patches of CT more effectively than sheep, and, at higher stocking rates, may improve the control of treatments like mowing (Hartley and Thomson 1981).

It is obvious that CT is an aggressive weed that has been successful at entering and thriving in many areas around the world. While much is known about the biology of CT, and how to manage it in cropland, little research has been done in regards to CT populations in permanent vegetation. IPM in pastures needs to be explored to find successful ways to deal with this invasive and economically important weed. Options that enhance known controls, and new control methods that can be used when chemicals are not an option need to be examined for effectiveness.

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3. CANADA THISTLE RESPONSE TO FORAGE DEFOLIATION INTENSITY AND FREQUENCY

3.1 Introduction

The incidence and abundance of weeds in permanent pasture and rangeland often depends on the presence of microsites favoring weed invasion, which provide opportunities for weed spread. Decreased vigor of the desirable forage community creates areas of entry and amplification for undesirable weeds, as light, water, space and nutrients become available to those plants that have an inherent ability to make use of such resources (Edwards et al. 2000; Heimann and Cussans 1996; Ang et al. 1994; Thrasher et al. 1963; Bakker 1960). Despite knowledge of the competitive relationships between desirable and undesirable species in pasture communities, little is understood of the effect defoliation regimes have on altering this dynamic by manipulating competitive relationships between forage and weed populations, and their implications for land management.

In western Canada, Canada thistle [*Cirsium arvense* (L.) Scop.] has been recognized as one of the most problematic weeds, in both cultivated fields and permanent pastures (Doll 1984; Peschken et al. 1982; Schröder 1980; Holm et al. 1977; Maw 1976; Dewey 1901), and has been shown to reduce forage yield in pastures (Grekul and Bork, in press). This plant is highly competitive due to its extensive root system and vigorous growth strategy (Donald 1990; Schlichting 1986; Holm et al. 1977; Moore 1975;

Hodgson 1968; Hamdoun 1967; Bakker 1960; Hayden 1934; Detmers 1927). The spread of Canada thistle (CT) into pastures largely depends on the resulting competitiveness of the forage stand. CT can be controlled using herbicides (Grekul 2003; Donald 1990; Turnbull and Stephenson 1985; O'Sullivan and Kossatz 1982; Hunter and Smith 1972; Chang and Vanden Born 1968, 1971), with fertilization enhancing the degree of control (Grekul 2003; Bourdôt 1996; Donald 1990; Hume 1982; Thrasher et al. 1963; McKay et al. 1959), presumably by increasing forage vigor, enabling the desirable species to compete more effectively against the weed. The addition of defoliation as a specific disturbance to pasture communities may alter CT abundance by modifying forage vigor and associated weed-forage interspecific competition.

Continuous (or season-long) grazing systems maximize animal selectivity, leading to patchy use (Crawley 1983), with some areas under-utilized, and other areas over-utilized. Stressed plants in heavily used patches will create a more susceptible community for weed invasion because of low competitive fitness. Moreover, bare soil that occurs in these patches (with over-grazing) provides microsites for invasive weed entry (Heitschmidt and Stuth 1991; Crawley 1983). Growth of CT is enhanced by low palatability to grazers, including cattle (Wood 1987; Oswald and Brockman 1985). Avoidance of CT favors these plants with greater leaf area (optimize Ps output and growth), giving a distinct competitive advantage to CT, and increasing grazing pressure on surrounding palatable species. The decline in surrounding vegetation further enhances the competitiveness of CT through increased access to water, nutrients and light, promoting its vigor and spread. This feedback cycle is enhanced by continuous, selective grazing pressure (Edwards et al. 2000; Heimann and Cussans 1996; Ang et al. 1994; Thrasher et al. 1963; Bakker 1960).

There are two general grazing strategies that livestock producers can use to promote pasture vigor while making use of forage, although neither have been rigorously tested for application in weed control. Both are reflected in the use of a rotational system where there is an increase in grazing pressure (i.e. ratio of instantaneous forage demand to supply), leading to a potential decrease in animal selectivity. The first is known as a high intensity, low frequency (HILF) grazing system, where high stocking densities are employed over short periods to intensely defoliate forage, and is followed by a long recovery period. While the HILF system has the possibility of impacting CT directly, as it is designed to help overcome animal selectivity for palatable forage plants (Heitschmidt and Stuth 1991), it may also reduce forage plant vigor. The second is represented by a short duration (SD or low-intensity, high-frequency) system, where forage is lightly defoliated, and followed by a short recovery before regrazing (Heitschmidt and Stuth 1991). Despite little direct use of CT, light defoliation is thought to temporally maximize forage vigor as it stimulates new plant growth, resulting in maximum competitive pressure against weeds.

The purpose of this study is to experimentally test whether: (1) different forage defoliation regimes that simulate selective continuous grazing (HIHF or high frequency-high intensity), short duration grazing (SD or low intensity-high frequency), high intensity grazing (HILF or high intensity-low frequency) or deferred grazing (biomass removed late in the growing season) can influence CT density and biomass, and (2) simulated grazing regimes affect the accumulated, season-long forage production of pasture vegetation. This information should lead to an improved understanding of how the timing and intensity of defoliation, as determined by various grazing systems, can alter weed-forage competitive relationships, and ultimately minimize CT abundance.

3.2 Materials and Methods

3.2.1 Study Area

Replicated plots were located at each of four sites across central Alberta, Canada, between 1999-2001. All sites were located in the Aspen Parkland Ecoregion (Strong 1992), and were selected for their suitability to evaluate the impact of defoliation regime and subsequent sward vigor on CT abundance under fertilized and unfertilized conditions. All sites had abundant CT populations spread relatively uniformly over the study area, had little internal variation in slope and aspect (Table 3.1), and were known to be free of chemical control in the previous three years. Sites were located on pastures in the Counties of (1) Lamont, (2) Two Hills, (3) Barrhead and (4) Clearwater (Table 3.1). Dominant grass species consisted of smooth brome (*Bromus inermis* Leyess.), Kentucky bluegrass (*Poa pratensis* L.) and quackgrass [*Agropyron repens* (L.) Beauvois]. Major non-thistle forb species were dandelion (*Taraxacum officinale* Web.) and white clover (*Trifolium repens* L.), with the Two Hills and Clearwater sites containing American vetch (*Vicia americana* Munlenb.), and the Clearwater site containing tall buttercup (*Ranunculus acris* L.). Three of the four sites were located on Black Chernozemic soils (Table 3.2), while the fourth was on an old river floodplain with a Humic Gleysol (Table 3.2). All sites were fenced around the treatment area to prevent animal defoliation and facilitate data collection. Soil samples were collected in May of 1999, 2000 and 2001 from four locations randomly distributed across the site, then pooled prior to lab analysis. Two depths were sampled (0-15 and 15-30 cm) and sent to Norwest Labs for analysis. Each depth was analyzed separately and averaged following analysis. Nitrogen (nitrate), phosphorus (phosphate), and potassium were analyzed according to the methods of Ashworth and Mrazek (1995). Sulfur (sulfate), organic matter, pH, electrical conductivity, and particle size were conducted using the methods of McKeague (1978) (Table 3.2).

3.2.2 Experimental Design and Defoliation Treatments

At each site, a split-block experimental design was established to assess the influence of non-CT forage defoliation intensity and frequency, with and without fertilization, on accumulated forage production and associated CT abundance. Within each site, two whole plots measuring 10 X 10 m in size were established, one of which was randomly selected for annual fertilization during May. Fertilization rates were 100-45-10-15 $kg \cdot ha^{-1}$ of N-P-K-S in each of the three years (1999, 2000, and 2001), and were applied between 15 May and 31 May. Although fertilizer was initially to be applied at rates specified by soil testing, nutrients added at the beginning of each growing season within each site were often depleted one year later. Given the importance of eliminating these macronutrients (by fertilizing to soil test requirements) as a limiting factor for plant (weed and forage) growth, consistent fertilization treatments were used rather than variable treatments.

Within each of the four sites, 20, 1 x 1-m subplots were systematically established in each of the fertilized and unfertilized whole plots, for a total of 160 subplots. Four defoliation regimes were then applied to five randomly selected replicate subplots in each whole plot, with each defoliation simulating a unique grazing system. Grazing systems included continuous (simulated through high intensity, high frequency), HILF (high intensity, low frequency), SD (short duration: low intensity and high frequency), and deferred defoliation (until peak growth in mid to late August). Defoliation (i.e. clipping) regimes were randomly assigned to subplots within whole plots, and included the following treatments administered from 15 May to 31 August:

1] Continuous – subplot forage (i.e. vegetation excluding CT) clipped to a height of 2 cm every 2 weeks.

2] SD – subplot forage clipped to a height of 10 cm every 2 weeks.

3] HILF – subplot forage clipped to a height of 2 cm every 6 weeks.

4] Deferred – subplot forage clipped once at the end of the growing season (mid-August) to evaluate maximum forage production in the absence of early or mid-season grazing.

Vegetation growth after 31 August was assumed to be negligible as this corresponds to the late growing season in central Alberta, often after the first killing frost (normally occurring in early September). For a site map, see Appendix One.

3.2.3 Vegetation Measurements

All vegetation measurements were made within a 0.25 m^2 area (50 X 50-cm) nested within the 1 m^2 subplot. This procedure maintained a 25 cm defoliated buffer zone around the sampled area and helped ensure treatment (i.e. defoliation) responses were not influenced by the condition of adjacent vegetation. Subplots at three of the sites were sampled in late August of 1999 for initial CT abundance (density and phytomass) and maximum CT height, which was obtained by measuring the tallest CT stem within each nested sample area. Year-end herbage biomass was measured by harvesting grass, CT, and non-CT forbs at the end of the growing season to ground level. These values served as a baseline to adjust observed vegetation responses in years two and three during implementation of the various defoliation regimes on these same subplots. Baseline data could not be collected from the fourth site because wildlife broke the fence and allowed cattle to enter the study site in early August, just prior to sampling.

In 2000 and 2001, the scheduled defoliation treatments were applied to each subplot from 15 May to 31 August, with defoliation prior to 15 August occurring only on the non-CT component of each subplot. All biomass removed during the application of treatments within each permanent subplot was separated into grass and forb components, and accumulated throughout the growing season. After 15 August, all remaining grass and forb biomass was harvested to ground level and added to the material removed during the growing season. All herbage samples were dried at 50°C for 72 hr, and weighed to determine dry matter (DM).

In order to evaluate CT responses to non-CT herbage defoliation, the treatments imposed in 2000 and 2001 were designed to mimic cattle selectivity, under the assumption that CT is specifically avoided during grazing periods. Therefore, CT plants in each nested subplot were not harvested until 15 August after growing unimpeded through most of the growing season. Maximum height (measured the same as above) and stem density of CT were measured within each nested subplot, along with above ground CT biomass. Defoliation of CT in all years was uniform across all treatments within a site and year, and followed flowering and the onset of dormancy. Consequently, defoliation was assumed to have little influence on future abundance of CT within subplots, and no regrowth of CT at the end of the growing season (after defoliation) was observed.

At each site, whole plots were exposed to dormant season grazing in September and October of each year to prevent excessive litter accumulation and maintain otherwise normal land use activities. It was important to control litter build-up as it would advantage the grass component, increasing competition with CT in all treatments, which may have reduced the impact and differences seen amongst the applied treatments.

3.2.4 Data Analysis

All data were initially tested for normality using Proc Univariate (SAS Institute Inc. 1988) and the Kolmogorov-Smirnov test, and found to be normal ($P \geq 0.05$). Data were then analyzed in two steps. A preliminary analysis was conducted using a split-split-block analysis of variance (ANOVA) using Proc MIXED, with the 1999 initial baseline data included as covariates. Sites were used as reps, and at each site, whole plots were the fertilization treatments and subplots the defoliation treatments, with year of sampling the final split. Proc MIXED was used as it is better able to the handle unbalanced data, created by the loss of site 1 in 1999, and site 4 in the last year of sampling. However, this analysis consistently demonstrated no significant ($P \geq 0.05$) higher order interactions containing both year and the defoliation treatments for CT biomass, height, and density, or grass or forb biomass. Similarly, no covariate effect ($P \geq 0.05$) was found for this analysis for any of the response variables other than the forb biomass in 2000.

There were no significant interactions involving year and defoliation, indicating that year had no effect on the treatment effects observed. Also, since the data in site four was lost in 2001, if these data were analyzed using year, the degrees of freedom would drop from 3 to 2, which would weaken the analysis. As a result, data from 2000 and 2001 were analyzed separately with ANOVA. This had the advantage of clearly differentiating between immediate (first year) and longer-term (second year) effects due to defoliation regime. For this analysis, both Proc MIXED and Proc GLM were initially used, although the results were the same for both procedures. As a result, Proc GLM was chosen because more interactions could be evaluated. The baseline 1999 data were again included as a covariate, although only initial forb biomass had a significant ($P<0.05$) impact, and only within the 2000 analysis (Table 3.3).

Grass, forb and CT biomass, together with CT height and density from each year (2000 and 2001) were each analyzed to evaluate the temporal pattern of vegetation responses to the imposed defoliation treatments. Emphasis during analysis was placed on defoliation effects and its interaction with fertilization and site. In 2001, only three sites were tested as premature cattle grazing at site four prevented sampling of vegetation responses. Post-hoc mean comparisons using Tukey's method were conducted for all significant ($P \leq 0.05$) F-test main effects and interactions that included defoliation as a treatment. All mean analysis presented was conducted using least significant (LS) means.

3.3 Results

During 2000 and 2001, data analysis showed no significant ($P \leq 0.05$) covariate effects from 1999 CT biomass, density and height, nor grass biomass (Table 3.3), indicating that initial vegetation characteristics did not influence the observed responses. There was, however, a significant ($P \leq 0.05$) covariate response for non-thistle forb biomass in 2000 (Table 3.3) that likely occurred because only one site (site four) had a major forb component other than CT. As site four was lost in 2001, this probably accounts for the absence of a significant covariate effect for forb biomass in 2001. Fertilization and site effects were sometimes significant ($P \leq 0.05$), but will only be discussed where there is a significant ($P \leq 0.05$) interaction with the defoliation treatments.

3.3.1 Canada Thistle Response

In 2000, CT density showed a site by fertilization interaction, defoliation, and defoliation by site ($P \leq 0.05$) effects. In contrast, there were no significant effects ($P \leq 0.05$) for CT biomass in 2000 (Table 3.3). One year later during 2001, there were more complex interactions, with significant ($P \leq 0.05$) site by fertilization, defoliation, defoliation by site and defoliation by site by fertilization effects (Table 3.3) for both thistle density and biomass. When year effects were analyzed in isolation, there were significant year ($F=12.9$; $P \leq 0.01$) and year by site ($F=25.7$; $P \leq 0.0001$) effects for CT biomass. Similarly, CT density also had a significant year ($F= 12.4$; $P \leq 0.01$) and year by site (6.3; $P \leq 0.01$) effect. In 2000 and 2001, CT density was 13.1 and 10.3 $\text{stems}\cdot\text{m}^{-2}$, while CT biomass was 1282 and 847 kg·ha^{-2}, respectively across all sites (data not shown). This trend was due to site 2, where CT biomass and density both decreased in 2001. There was no difference in sites between years for CT density, while at site one, CT biomass actually increased in 2001.

Across all sites, the continuous defoliation treatment consistently had significantly ($P \leq 0.05$) greater CT density and biomass than the other defoliation treatments, a trend observed in both 2000 (density only) and 2001, under both fertilized and unfertilized conditions (Table 3.4). In contrast, the deferred defoliation treatment consistently resulted in significantly ($P \leq 0.05$) lower CT density and biomass for both years (Table 3.4). Between defoliation regimes simulating rotational grazing, the HILF treatment had less CT density and biomass than the SD treatment.

The interaction of fertilization with defoliation indicated that fertilization resulted in greater differences among defoliation regimes, particularly the SD from either the continuous or HILF treatments (Table 3.4). The defoliation by site by fertilization effects indicated there were some site variations in showing significant treatment differences, while still representing the general trend described above. Primarily, the main difference was observed at site three, where there was no significant ($P > 0.05$) treatment differences for CT density in both fertilized and unfertilized plots, as did site four in the unfertilized plots in 2000 (data not presented). At site one, there was no significant ($P > 0.05$) difference between the HILF and deferred treatments for both CT density and biomass. Site two showed no significant ($P > 0.05$) difference in CT density between the SD and HILF treatments in fertilized plots, and no significant differences between continuous and SD treatments in unfertilized plots (Table 3.4). There were also no significant ($P > 0.05$)

density differences between the HILF, SD, and deferred treatments in the fertilized plots of site four in 2000.

CT biomass followed the same trends seen in CT density, with some site differences. In 2001, site three showed no significant ($P>0.05$) treatment differences for CT density in both fertilized and unfertilized plots, as did site two in the fertilized plots (Table 3.4). At site four in 2000, the deferred treatment had significantly ($P\leq0.05$) greater CT biomass than all other treatments in the fertilized plots, and the SD and deferred treatments had significantly greater CT biomass than the continuous and HILF treatments in the unfertilized plots (data not presented).

CT height in 2000 displayed a significant ($P\leq0.05$) site by fertilization interaction and a defoliation treatment effect. The deferred treatment had significantly ($P\leq0.05$) taller CT than all other treatments, while the continuous had the shortest CT (Figure 3.5). In 2001, the only significant ($P\leq0.05$) effect observed in relation to CT height was site by fertilization. However, a defoliation by fertilization effect was nearly significant ($P = 0.07$). CT heights were also generally taller in 2001 than in 2000. In fertilized plots, there was no significant ($P\leq0.05$) difference between treatments. However, in unfertilized plots, the deferred treatment had significantly ($P\leq0.05$) shorter CT than the continuous and SD treatments, with no significant difference between the HILF and the other 3 defoliation regimes (Figure 3.6).

3.3.2 Forage Response

When year effects were included in the initial analysis, there were significant year ($F=19.6$; $P\leq0.0001$) and year by site ($F=32.6$; $P\leq0.0001$) effects for grass biomass, likely due to the accumulative effects of drought in 2000. In 2000 and 2001, grass biomass was 3078 and 3629 kg·ha^{-2}, while forb biomass was 184 and 96 kg·ha^{-2}, respectively. This trend of increased grass biomass was again due to site two, while the decrease in forb biomass in 2001 was similarly due to site two. Conversely, site one showed a decrease in grass biomass in 2001.

Grass biomass in 2000 and 2001 had significant ($P \leq 0.05$) fertilizer, defoliation, defoliation by site, and defoliation by fertilization effects (Table 3.3). In 2000, there was also a 3-way interaction between defoliation, site and fertilization ($P \leq 0.05$), while in 2001, there was an additional site effect ($P \leq 0.05$). There were no significant year interactions.

A comparison of LS means was done for all significant ($P \leq 0.05$) effects. Across all sites and fertilization regimes for each year, the continuous treatment had the least grass production. The observed trend for grass biomass production had the deferred treatment with significantly greater ($P \leq 0.05$) grass production than the other treatments, followed by the HILF and SD treatments, respectively (where HILF grass production was significantly ($P \leq 0.05$) greater than the SD treatment) (Figures 3.1 and 3.2). Slight variations of this trend occurred across site, fertilization and year. For example, in 2000 the unfertilized plots demonstrated no significant ($P > 0.05$) difference between the HILF and SD treatments. Additionally, sites two and three showed no significant difference in the fertilized plots between the HILF and SD treatments. In 2001, all sites and fertilization regimes followed the observed trend except the unfertilized plots at site three, where SD had the greatest production followed by the deferred and HILF treatments (data not presented).

Forb biomass in 2000 had significant site and defoliation by site ($P \leq 0.05$) effects. There was also a significant covariate ($P \leq 0.05$) effect in 2000. There were no significant forb biomass effects in 2001. As site four was the only site with a major forb component, when this site was lost in 2001, forbs were no longer a major component of the swards examined.

3.4 Discussion

3.4.1 Herbage Responses

Accumulated herbage yields responded to defoliation treatment, fertilization, and site, often in combination with one another. The greatest grass yields occurred with deferred defoliation, followed by the HILF and SD defoliation regimes, and then the intensive, continuous defoliation pattern. Moreover, differences among defoliation treatments were consistent regardless of fertilization, and were evident immediately during the first year. Differences between defoliation treatments, particularly the HILF and SD regimes, did become more pronounced in the second year. The increased response in the second year indicated that there was a cumulative effect associated with the forage responses to the defoliation treatments implemented, likely due to gradual changes in forage plant vigor, more positive in the HILF and deferred treatment, and negative in the continuous.

Among treatments, deferred defoliation allowed for the longest uninterrupted rest period before initial defoliation, and suggests any defoliation during the growing season will decrease total production. This result is in contrast to other studies in the Aspen

Parkland of western Canada where compensatory growth (i.e. overyielding) has been demonstrated with intermittent defoliation simulating HILF and SD grazing (Donkor et al. 2002). However, because both 2000 and 2001 were characterized by relatively dry conditions across all sites (Table 3.1), and compensatory growth occurs when soil moisture is not limiting (Whitman 1987; Belsky 1986; Hart and Balla 1982; McNaughton 1979; Paige and Dyer and Bokhari 1976), it is possible the deferred regime tested here made more efficient use of the limited available soil moisture.

In sharp contrast to the deferred treatment, continuous defoliation consistently produced the least grass biomass in both years and each fertilization treatment. Intense, frequent defoliation does not appear to allow for adequate grass recovery to maintain plant vigor and sustained rapid growth. Loss of vigor, in turn, reduced grass yield. Associated increases in CT within these plots may further stress forage plants through intense competition, enhancing the reduction of grass yield. Therefore, it was not unexpected that the continuous treatment would have the lowest grass production.

The HILF treatment resulted in the greatest production of the three defoliation regimes simulating grazing systems implemented during the growing season. Although grass and other forbs in this treatment were clipped to the same intensity of that applied in the simulated continuous treatment (which resulted in the least production), the extended rest period provided time for the plants to recover, increasing plant vigor and ultimately production. These results are consistent with other trials done on similar vegetation types (Donkor et al. 2002).

The lower grass yield in the SD treatment compared to the HILF treatment indicates that herbage growth is affected by both the intensity and frequency of defoliation. Moreover, the finding that the HILF regime consistently outyielded the SD treatment indicates that SD herbage yield was more heavily dependent on (or sensitive to) defoliation frequency rather than intensity (i.e. clipping height). In other words, sustained growth was greater when defoliation occurred infrequently, but at intensive levels. This result is somewhat surprising given that finite maximum use levels (e.g. 50-70% on tame pasture) are often recommended for pasture swards in order to maintain herbage vigor and production, which in turn, appear more likely to be met through the more conservative SD defoliation regime.

Although the detailed mechanism responsible for the greater grass yield associated with HILF rather than the SD defoliation is unknown, one possible explanation is that HILF defoliation may maintain the pasture swards examined at more rapid rates of vegetative growth. The dominant forage grasses at each of the study sites, including smooth brome, quackgrass, and Kentucky bluegrass, in general are well-adapted to defoliation. All these species have rapid growth rates and extensive underground rhizomes, characteristics that increase their tolerance to defoliation. Defoliation within the HILF regime, even at intense levels as high as 75% or more, may result in these grasses changing to a more rapid rate of growth (i.e. near the inflection point of curve A in Figure 3.4), which throughout the growing season, could lead to greater accumulated herbage yield through favorable regrowth. In contrast, conservative defoliation, albeit frequent, within the SD regime, may be less effective at maintaining these grasses within rapid stages of growth (Parsons et al. 1988) (top of curve A in Figure 3.4). Conservative levels of defoliation (e.g. less than 50%) may not alter the condition of these grasses sufficiently to maintain sustained rapid re-growth (middle of curve A in

Figure 3.4), leading to less season-long herbage yield despite light defoliation. Thus, in this study, the HILF defoliation regime appears to produce a type of compensatory growth pattern over the entire growing season within these pastures swards. Nevertheless, results may not be the same for plant communities that are not so well-adapted to withstand or recover from infrequent but intense defoliation events (see curves B and C in Figure 3.4).

While the continuous treatment also removed plant biomass at a 75-80% defoliation level, the short time period between defoliation events proved inadequate to facilitate recovery, and more rest time was required for plant recovery from the stress of defoliation. Because the HILF treatment is given extended rest between defoliation events, it allows grasses to recover morphologically and physiologically from intense defoliation, thereby producing more herbage. This may be, in part, due to the lag time that plants experience in growth after a defoliation event (Davidson 1979; Hodgkinson and Baas Becking 1977; Davidson and Milthorpe 1966; Troughton 1957). Increased grass biomass in the HILF treatments relative to the SD treatments may also have resulted from a decline in CT populations in the HILF treatments. This reduction allows for more total resources, like water, nutrients and light, to be utilized by grasses, enhancing their growth and yield abundance (for plot photos, see Appendix Two).

The unfertilized data generally showed the same trends among defoliation treatments as fertilized data, the difference being fertilization augmented differential response to defoliation. That is, the positive response of accumulated herbage yield in the rotational systems (SD and HILF) over that of continuous defoliation was enhanced by fertilization, with the greatest response within the HILF treatment. These results seem to indicate that grass utilization of added nutrients is maximized in intermittently defoliated systems, perhaps because grasses in the continuous system are being defoliated at such an intense level they are unable to make efficient use of available nutrients (Heitschmidt and Stuth 1991; Carman and Briske 1982; Richards 1984; Evans 1973; Jameson 1963; Biswell and Weaver 1933).

In 2000, defoliation effects were not distinct, with only the deferred treatment significantly different from the others for the majority of sites and fertilization treatments (with the exception of site one and four fertilized plots). This seems to indicate that at least two years of defoliation were required before distinct defoliation influences on grass production were observed. This was confirmed in 2001, where more distinct treatment differences were observed. The HILF treatment had more grass production than the SD treatment in all cases but one: site three in the unfertilized plots. Different site characteristics like initial vegetation composition and environmental conditions like moisture and nutrients may have altered the degree of defoliation needed to increase rates of regrowth, with the result that a less intensive level of biomass removal (e.g. 50%, curve B in Figure 3.4) resulted in more rapid regrowth at this site.

Forb production was not affected by defoliation treatment in either year. In the majority of subplots, the common forb species present were *Taraxacum officinale* and *Trifolium* sp., although most were not major components of the pasture community. Additionally, these species are known to be resistant to defoliation and usually appear in heavily defoliated areas (Jantunen 2003; Pavlu et al. 2003; Sanderson et al. 2002; Pavlu and Velich 2001; Singer et al. 2001; Pederson and Brink 2000; Klimes 1999; Rogalski et al. 1997; Davies et al. 1996). Favorable initial tolerance to defoliation is a possible reason why forbs were not negatively affected by variable defoliation. In addition, some forbs (e.g. vetchling) may have been 1) more affected by defoliation regardless of timing and intensity because their growing points are removed with any defoliation, and 2) affected very heavily by competition against the grasses, which had a highly significant response to defoliation.

3.4.2 Canada Thistle Response

Thistle density and end-of-year biomass displayed a trend opposite that of herbage production, with the greatest levels within the continuous treatment and the lowest levels in the deferred and HILF treatments. Because actual defoliation during the growing season was applied only to non-CT herbage, the differences observed between treatments are attributed to competitive weed-forage interactions influenced by the timing and intensity of non-thistle herbage defoliation, and not direct defoliation of CT. Moreover, because year-end CT biomass harvests were conducted at the end of the growing season when this species was approaching dormancy, defoliation at that time was assumed to have little impact on the subsequent response of that species, results which appear to be supported by the strong continued differences among defoliation treatments in successive years of the study.

Deferring grass defoliation until late in the growing season consistently decreased CT abundance more than any other treatment. Notably, this treatment also coincided with the greatest accumulated grass biomass. Uninterrupted grass growth during the growing season therefore appears to have minimized CT abundance, likely through maximal reductions in available light, moisture, and nutrients for developing CT stems.

The few CT stems found in the understory of these subplots were generally small, weak-stemmed, and chlorotic in appearance, symptomatic of exposure to sustained low light levels.

Conversely, the greatest CT biomass and density occurred in the continuous defoliation treatment. In these subplots, weakened grass plants from repeated defoliation with little recovery time, appeared to result in a significant competitive advantage for CT, leading to its increase. Under these conditions, undefoliated CT would be able to exploit the available resources, in turn contributing to the marked reduction in grass yield discussed earlier. In addition to sustained high levels of available light, repeated intense defoliation likely rendered the resident grasses susceptible to root mass reductions (Richards 1984; Carman and Briske 1982; Troughton 1981; Hodgkinson and Baas Becking 1977; Evans 1973; Jameson 1963; Weaver and Zink 1946; Biswell and Weaver 1933), decreasing their competitive fitness belowground. This mechanism likely accounts for the further increase in CT abundance within continuously defoliated subplots when fertilized. Added fertilizer would be preferentially taken up by the undefoliated CT plants and their extensive root systems. Positive CT responses to fertilization in the absence of weed control have been documented in other studies (e.g. Grekul 2003).

Next to the deferred treatment, the HILF defoliation regime had the least CT, followed by the SD treatment. These differences tended to increase into the second year, suggesting the defoliation regimes implemented required several years to manifest full defoliation treatment effects via competitive shifts between CT and neighboring plant species. Reductions in CT within the HILF and SD treatments are attributed to the longer recovery period (HILF) or reduced defoliation intensity (SD), and their associated increases in grass vigor and growth outlined earlier, leading to more intense competition with resident CT plants. Among the two treatments simulating summer grazing systems, the HILF regime led to greater CT reductions, perhaps because grasses in this treatment were kept in a more rapid stage of growth due to infrequent intensive defoliation. Maintaining non-CT herbage in a more rapid stage of growth would cause more intense competition between herbage, primarily grasses, and CT for light, water and nutrients. Moreover, these results suggest that belowground competitive processes may be dominant over aboveground processes. Although CT is sensitive to light restrictions (Jordan 1996; Pester et al. 1996; Donald 1990; Pook 1983; Medd and Lovett 1978), had this been the primary factor limiting CT growth in this study, the SD treatment should have resulted in the least CT, as reductions in light would have been greatest with the 10-cm SD defoliation treatment rather than the 2-cm HILF treatment. Given that the HILF regime resulted in lower CT abundance, but would have periodically resulted in high levels of light for CT vegetative stems, we hypothesize that intense belowground competition for water and nutrients were responsible for reducing CT abundance (for plot photos, see Appendix Two).

Fertilization generally served to augment the CT reduction in the HILF and deferred treatments seen in the unfertilized plots. Because grass was more vigorous and productive in the HILF and deferred treatments, these plants may have accessed the additional nutrients more effectively during the growing season, in turn increasing their competitiveness with CT. Variation in the effectiveness of fertilization was likely due to differences in the soils at each site, and the initial nutrients associated with them, differences in initial vegetational composition at each site, and the amount of moisture available to enable nutrients to be effectively utilized.

There were factors that limited the effectiveness of defoliation treatments and how they were expressed in both 2000 and 2001. There are two main reasons for this. First, site 4 was lost in 2001, altering the group of study sites being compared in each year. Second, significant drought periods occurred during the summer of 2000 and may have altered the patterns of defoliation treatment impacts on CT abundance. While there was less rainfall in 2001 (Table 3.1), the precipitation that did occur was arguably at more appropriate times, and conducive to maintaining continued plant growth than the previous year. Lack of moisture, particularly in 2000, may have limited the CT height responses to defoliation in this study.

Overall, these results indicate that both fertilization and the defoliation treatments examined are capable of altering the abundance of CT and associated herbage in central Alberta pastures. These results indicate that defoliation frequency, rather than intensity, appears to be the more important determinant of herbage (particularly grass) production and CT abundance. The pastures examined appear to be well-adapted to tolerate intense defoliation provided a long recovery period (around 6 wks) is provided to facilitate rapid growth and maintain plant vigor. This type of strategy is exemplified by the HILF grazing system.

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Table 3.1. Location, landscape characteristics, and growing season precipitation for the four defoliation study sites.

Site	Location	Slope/ Aspect	Landform	Precipitation (May-Aug; mm)				
				1999	2000	2001	30 yr av.	30 yr High/Low
1	Lamont	Level/ NA	Level Moraine	235	272	279	338	418/147
2	Barrhead	Level/ NA	Floodplain	281	301	292	440	644/205
3	Two Hills	<2%/ West	Hummocky Moraine	194	248	219	316	476/171
4	Clearwater	<2%/ West	Rolling Moraine	365	406	256	404	503/208

Table 3.2. Soil characteristics within each of the four defoliation study sites, as sampled in May, 1999[z].

Site	pH	E.C. $mS \cdot cm^{-1}$	O.M. (%)	Nutrients (kg ha^{-1})[y]				Texture (%)			Soil Type
				N	P	K	S	Sand	Silt	Clay	
1	6.9	0.5	10.1	47	7	428	33	38.6	44.0	17.4	Loam, Orthic Black Chernozem
2	6.7	2.9	33.5	130	11	1009	3289	49.2	33.3	17.5	Loam, Orthic Humic Gleysol
3	7.9	0.7	23.0	52	0	601	73	34.4	46.0	19.6	Loam, Gleyed Dark Gray Chernozem
4	6.0	0.2	11.0	11	7	798	16	28.0	49.7	22.3	Silt, Loam, Orthic Black Chernozem

[z] All values represent the average of two soil depths sampled and analyzed separately (0-15 and 15-30 cm). Nitrogen, phosphorous, and sulfur were present in the form of nitrate, phosphate and sulfate, respectively.
[y] Nutrients represent pre-fertilization data.

Table 3.3. ANOVA F-value results from Proc GLM for CT density, height, and biomass, as well as grass biomass showing significant effects for different defoliation regimes and fertilization treatments across four sites in each of 2 years (where F is fertilized and NF is non-fertilized).

		Thistle			Herbage	
	df	Density (#·m^{-2})	Biomass (kg·ha^{-1})	Height (cm)	Grass (kg·ha^{-1})	Forb (kg·ha^{-1})
2000						
1999 Covariate	1	0.04	4.56	0.45	5.15	55.28*
Site	2	2.57	7.15	6.3	10.01	22.11*
Fertilizer (Fert)	1	1.24	0.64	0.22	78.53*	1.64
Site X Fert	2	7.64***	1.76	4.69**	0.41	1.14
Defoliation (Def)	3	12.16***	2.12	6.31**	33.56***	0.51
Def X Site	6	2.39*	0.65	1.77	2.52*	2.09*
Def X Fert	3	1.95	1.33	1.58	5.27**	0.71
Def X Site X Fert	6	1.72	0.7	0.37	2.52*	1.01
2001						
1999 Covariate	1	0.00	0.00	0.61	0.00	1.00
Site	1	1.66	0.42	6.42	111.62**	0.73
Fert	1	0.02	0.46	0.82	128.32**	0.19
Site X Fert	1	11.22***	7.76**	4.34*	1.18	1.78
Def	3	11.89***	11.94***	0.9	47.97***	1.34
Def X Site	3	3.39**	3.78*	2.05	3.85**	0.11
Def X Fert	3	1.88	1.35	2.47	4.63**	1.02
Def X Site X Fert	3	2.36*	4.6**	1.38	1.25	1.23

*, **, *** Indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.0001$, respectively.

Table 3.4. Mean CT density and biomass for different defoliation regimes and fertilization treatments in 2001[1].

		Defoliation				
Site	Fert	Continuous	SD	HILF	Deferred	SE
				Density (#·m^{-2})		
1	F	147.2 a	76.8 b	48.0 c	37.6 c	11.7
	NF	54.4 a	58.4 a	35.2 ab	19.2 b	11.7
2	F	52.8 a	29.6 ab	32.0 ab	24.0 b	11.7
	NF	68.8 a	64.8 a	48.8 a	11.2 b	11.7
3	F	16.8 a	12.0 a	20.8 a	8.8 a	11.7
	NF	34.4 a	24.8 a	33.6 a	24.8 a	11.7
All	F	72.2 a	39.4 b	33.6 bc	23.5 c	17.0
Sites	NF	52.4 a	49.3 a	39.2 a	18.6 b	17.0
				Biomass (kg·ha^{-1})		
1	F	4520 a	2688 b	544 c	480 c	366.5
	NF	1344 a	1048 a	688 ab	108 b	366.5
2	F	1068 a	960 a	1060 a	872 a	366.5
	NF	1636 a	1264 a	772 ab	176 b	366.5
3	F	291 a	60 a	83 a	28 a	366.5
	NF	192 a	116 a	168 a	80 a	366.5
All	F	2730 a	1812 b	738 c	594 c	586.0
Sites	NF	1547 a	1182 ab	806 bc	205 c	586.0

[1] Within a row, defoliation means with different letters differ, $P \leq 0.05$.

Figure 3.1. Mean (SE) grass biomass for different defoliation treatments under fertilized and unfertilized conditions across four sites in 2000 (A) and 2001 (B). Within a year and fertilization treatment, defoliation regimes with different letters differ, P≤0.05.

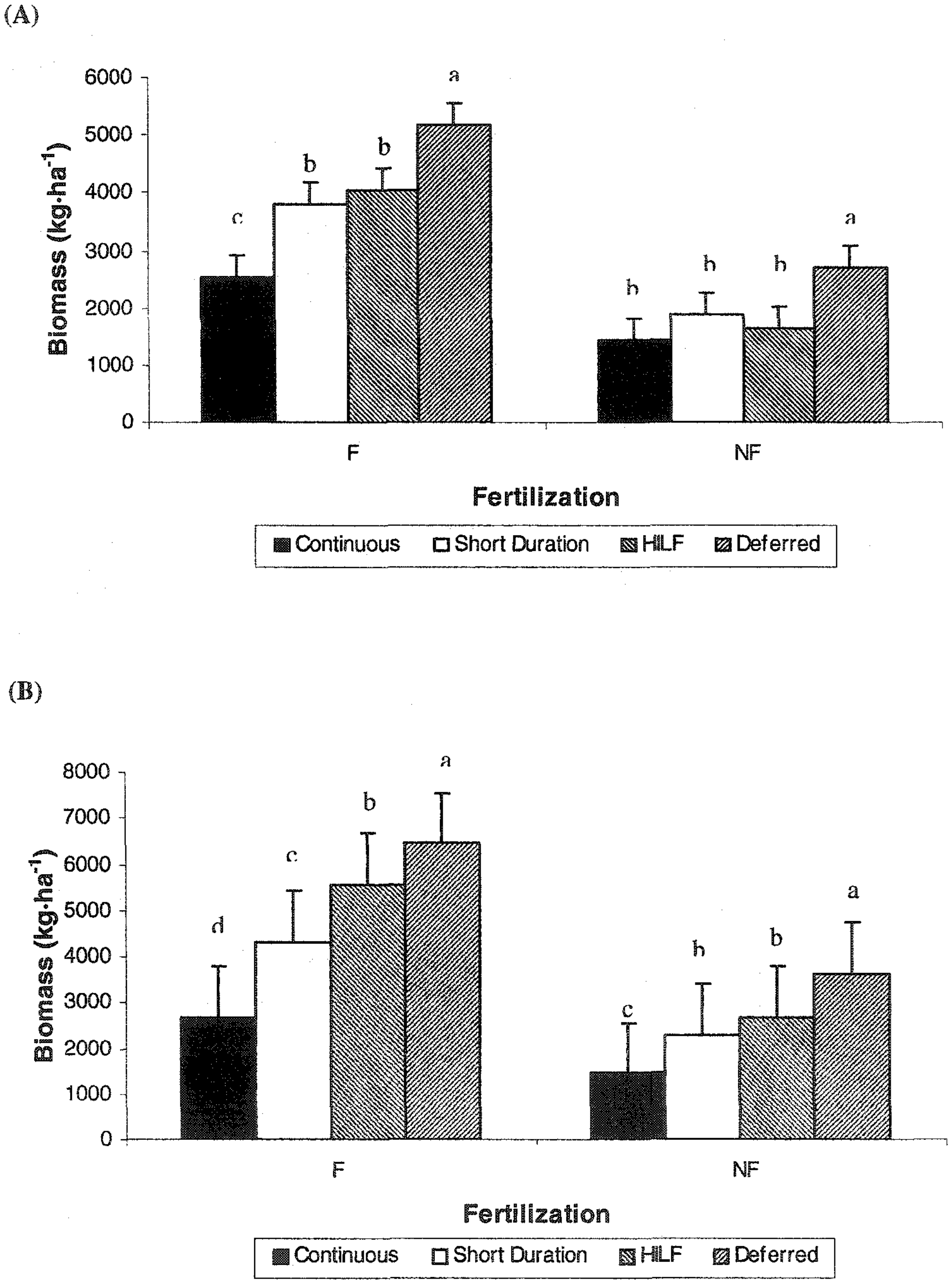


Figure 3.2. Mean (SE) CT biomass (A) and density (B) for different defoliation treatments at four sites in each of 2000 and 2001. Within a year, defoliation treatments with different letters differ, P≤0.05.

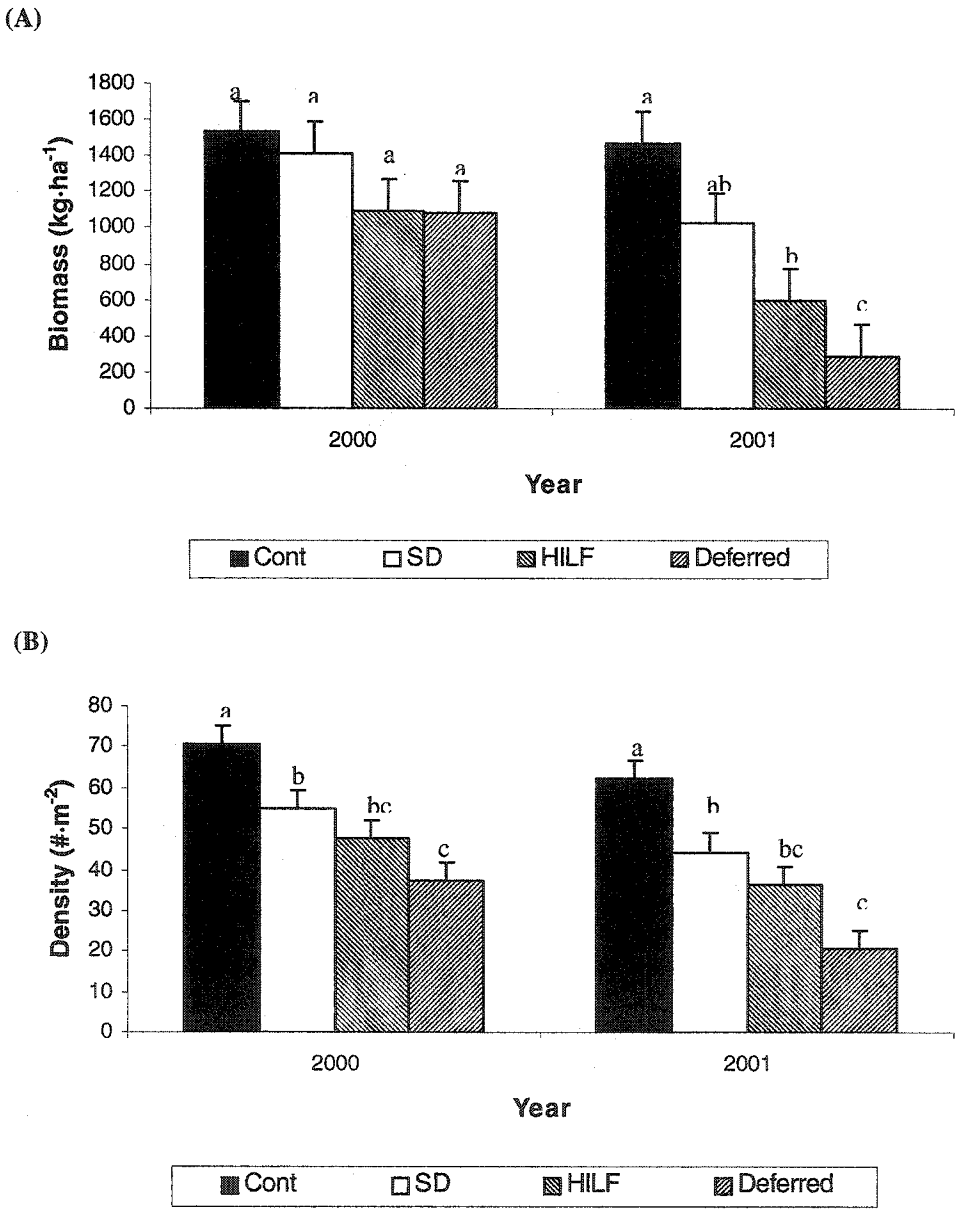


Figure 3.3. Mean (SE) CT height for different defoliation and fertilization treatments in 2000 (A) and 2001 (B). Within a year and fertilization regime, defoliation treatments with different letters differ, P≤0.05.

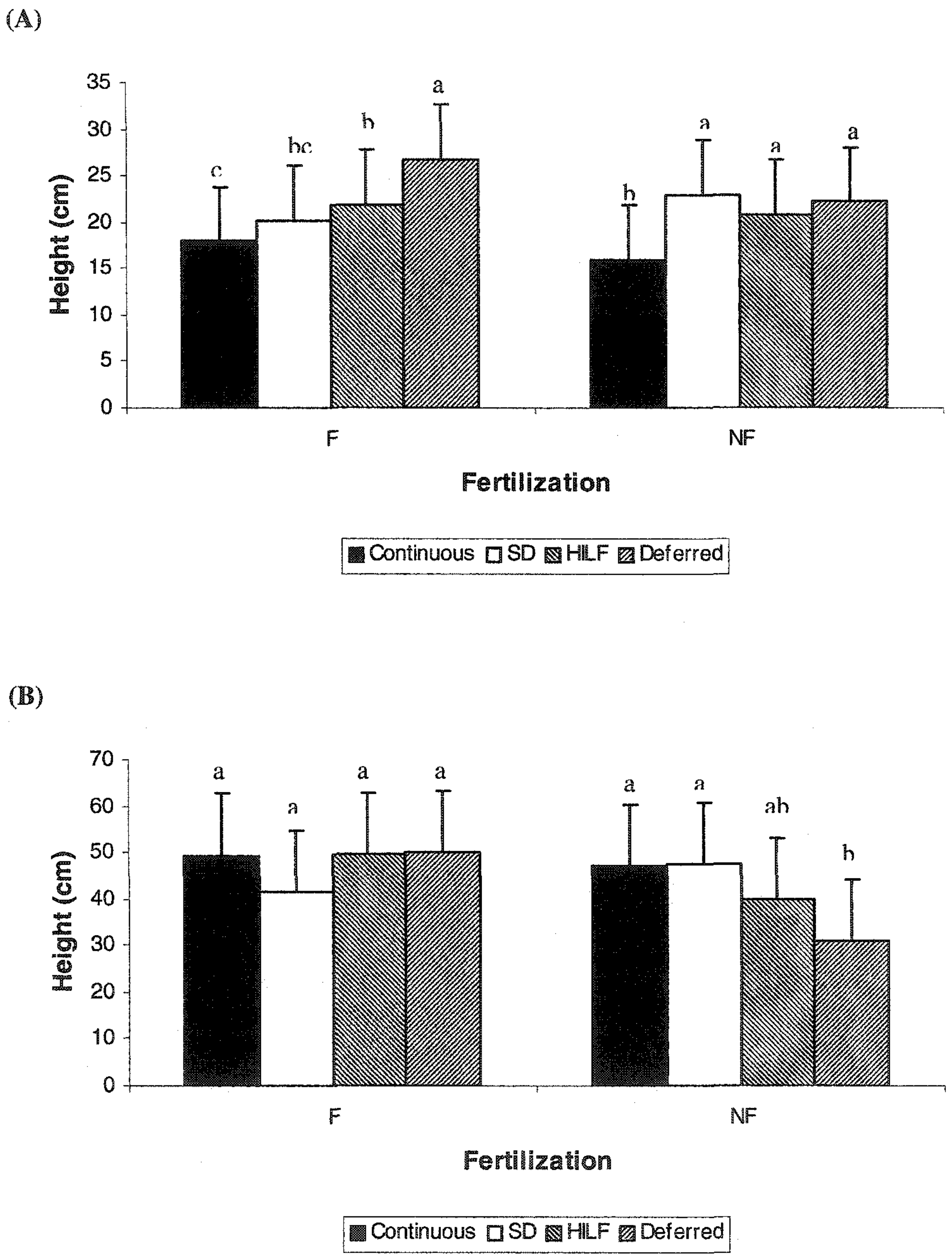
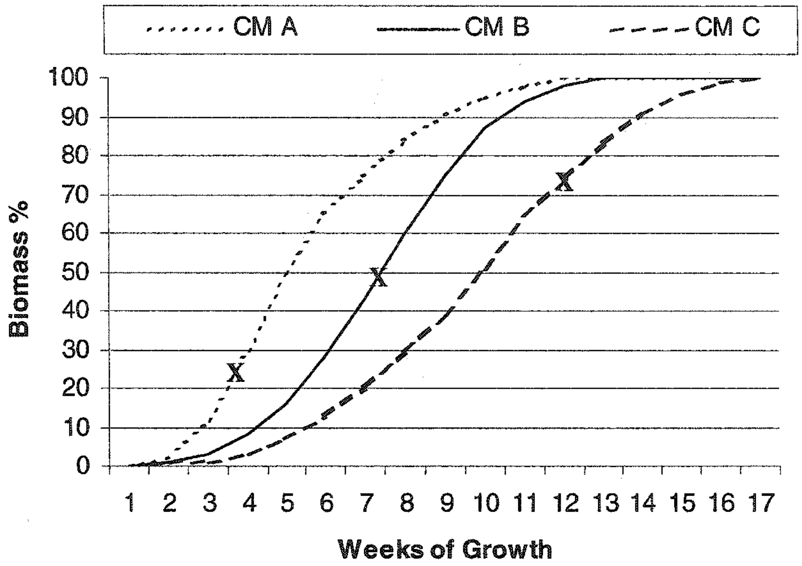


Figure 3.4. Hypothetical growth rates (as % accumulated biomass over time) for three different community (CM) types that respond differently to utilization level[1] as a result of their mean tolerance to defoliation.



[1] X – Represents the hypothetical inflection point on each curve where the remaining biomass after defoliation is expected to result in the most rapid rate of regrowth.

4. BIOCONTROL OF CANADA THISTLE USING DIFFERENT GRAZING REGIMES

4.1 Introduction

Canada thistle [*Cirsium arvense* (L.) Scop.] has been widely recognized as a problem weed, both in annual cropland and perennial pasture (Doll 1984; Peschken et al. 1982; Schröder 1980; Holm et al. 1977; Maw 1976; Dewey 1901). This plant is highly competitive due to its extensive root and shoot growth (Donald 1990; Schlichting 1986; Holm et al. 1977; Moore 1975; Hodgson 1968; Hamdoun 1967; Bakker 1960; Hayden 1934; Detmers 1927). In situations where the maintenance of continuous permanent cover is an important management objective, weed control can be difficult because it excludes mechanical methods, which would cause a temporary reduction in available forage and necessitate costly forage re-establishment.

Although many herbicides are effective in controlling CT (Grekul 2003), they may also kill desirable broadleaf pasture species, including nitrogen-fixing legumes (Peterson and Parochetti 1978; Amor and Harris 1977). Mowing is relatively ineffective for CT control, unless repeated several times annually over several years (Wilson and Kachman 1999; Hartley and James 1979; Amor and Harris 1977; Schreiber 1967; Thrasher et al. 1963; Derscheid et al. 1961; Hodgson 1958,1968; McKay et al. 1959; Welton et al. 1929; Detmers 1927). Infrequent mowing has been shown to increase the density of thistle stems (Grekul 2003; Amor and Harris 1977). Moreover, because pastures are often topographically irregular, it is difficult for vehicle mounted sprayers, towed sprayers, or mowers to access CT infested areas. Difficulty in controlling CT can also occur in and around areas where spraying is prohibited such as riparian areas, as well as protected areas or organic farms. As a result, weed bio-control has been increasingly explored for the management of CT, which includes the use of insects, diseases and other stressor agents.

Although CT is low in palatability, the plant is non-toxic to animals and can be relatively high in forage quality, including crude protein (Marten et al. 1987). While there are several examples of effective bio-control with other common range and pasture weeds such as leafy spurge (Lym et al. 1997; Walker et al. 1994; Landgraf et al. 1984; Bowes and Thomas 1978), efforts to control CT using biological efforts have been variable, with most demonstrating only a modest reduction (DiTomaso 2000; Donald 1990; Trumble and Kok 1982). In the US and other countries (like Australia), goats and sheep have been successfully used for CT control, and in some instances, cattle as well (Popay and Field 1996; Thomson and Power 1993; Donald 1990; Hartley and Thomson 1981; Amor and Harris 1975).

Many previous studies have shown that weeds can enter an area following livestock selection and overgrazing (DiTomaso 2000; Sutherst 2000; Hobbs and Huenneke 1992; Callihan and Evans 1991; Hobbs 1989, 1991, 2000; Mack 1989; Reece and Wilson 1983). However, livestock grazing has also been used as a tool for the control of weeds such as CT, although this generally uses sheep and goats with cattle only being recognized as a potential control agent (DiTomaso 2000; Sheley et al. 1998). In general, rotational grazing has the potential to reduce weed spread, while continuous grazing allows for rapid weed invasion and spread (Hartley 1983; Trumble and Kok 1982; Bendall 1973; Feldman et al. 1968), presumably by creating microsites for weed entry and propagation. The type and magnitude of changes in vegetation depend on the season (i.e. timing) of grazing, length of the grazing period, and defoliation intensity (Bullock et al. 2001; Donkor et al. 2001). For weed control, it is essential to time grazing to coincide with the point when the weed is most susceptible to defoliation, and when the coincidental impact on desirable vegetation is minimal (Kennett et al. 1992). Olson (1999) described three grazing strategies for managing weeds: (1) moderate grazing to minimize the physiological impact on native plants and reduce soil disturbance; (2) intensive grazing to counteract inherent dietary preferences of cattle such that the physical impact on weeds and desirable species is equal; and (3) multispecies grazing that distributes the impact of livestock grazing more uniformly among desirable and undesirable plant species.

Most previous research has restricted or excluded cattle grazing as a means to control CT, or where cattle were used, employed basic comparisons to other species (like sheep). In Canada, and more specifically Alberta, sheep and goats are uncommon on pastures and rangelands. Given that cattle are the primary grazers of much of the pasture across western Canada, it is essential to evaluate their impact on weeds such as CT and their associated potential as a bio-control tool. Similarly, no studies have used cattle alone in a high-intensity, low-frequency system intended to achieve forced defoliation of CT.

The purpose of this study was to test whether different grazing systems implemented for a 2-3 year period, could be used to alter the abundance of CT within permanent pastures of the Aspen Parkland region in central Alberta, Canada. In particular, we tested three different grazing systems including (1) continuous or season-long grazing, (2) short duration (or low intensity-high frequency) rotational grazing, and (3) HILF (high intensity-low frequency) rotational grazing, for their ability to reduce CT abundance and release non-CT herbage production. We also evaluated residual weed responses following the cessation of each rotational grazing treatment. A secondary objective was to evaluate season-long changes in the forage quality of CT plants throughout the growing season, and assess if this characteristic was altered through the use of different grazing systems.

4.2 Materials and Methods

4.2.1 Study Area

This study was conducted at four sites across the Aspen Parkland eco-region (Strong 1992) of central Alberta. Two sites were initially established in 2000 as a preliminary assessment of the ability of cattle grazing systems to control CT abundance in permanent pasture. One year later in 2001, two additional sites were added, with grazing treatments conducted at all four sites through 2002. These sites were located at (1) Wetaskiwin (riparian), (2) Westakiwin (dryland), (3) Rich Valley, and (4) Rimbey. All sites were selected based on uniformity in ecosite characteristics (e.g., slope, aspect, soil texture, drainage, etc.) and were sufficiently large to facilitate grazing. Additionally, each site had relatively uniform stands of abundant CT across a portion of the pasture where treatment paddocks could be established. While initial CT density differed among study sites (Table 4.1), no chemical or mechanical control had been applied in the previous three years. Precipitation levels for 2000-2002, as well as site location and landform characteristics are provided in Table 4.2. Dominant grass species usually consisted of smooth brome (*Bromus inermis* Leyess.), Kentucky bluegrass (*Poa pratensis* L). and quackgrass [*Agropyron repens* (L.) Beauvois]. Major forb species were dandelion (*Taraxacum officinale* Web.) and white clover (*Trifolium repens* L.), with sites 2 and 4 having greater forb abundance than the other two. All four sites were located on Orthic Black Chernozemic soils (Agriculture Canada Expert Committee on Soil Survey 1987).

4.2.2 Experimental Design and Grazing Treatments

Each pasture at all four sites had a recent history of being continuously (season-long) grazed during the summer by beef cattle, and therefore provided the continuous treatment at each site. Within each pasture, two smaller sub-pastures, 0.8 to 3.2 ha in size, were established using electric fencing, and randomly assigned either a HILF or SD grazing treatment. Continuous grazing represented the existing, or check treatment, at all experimental sites. Each grazing period of the SD treatment was implemented using the "put and take" method with a conservative target safe use level of 50%, whereby no more than half the available above ground biomass was removed during any single grazing period. Thus, SD grazing was implemented similar to the method local cattle producers would utilize, by visually estimating when cattle had consumed approximately half the available forage. Following grazing, SD pastures were rested up to four weeks, or until grass regrowth was satisfactory, at which time cattle once again grazed the sub-pasture (Table 4.3). Satisfactory regrowth was the point where biomass increases were approximately double that left after grazing.

When implementing the HILF treatment, cattle were generally left in the sub-pasture until CT was heavily impacted, regardless of the level of utilization on non-CT herbage. As a result, the HILF treatment used a longer grazing period than the SD treatment (approximately twice as long), leading to greater herbage utilization. However, heavy utilization was then followed by an extended recovery period before regrazing. Extended rest has been shown elsewhere in central Alberta to be essential to the ability of grasses to recover, remain vigorous and maximize production (Donkor et al. 2001). After grazing, HILF sub-pastures were rested for 8-9 weeks, although the exact length of the rest period was modified according to the rate of grass growth (Table 4.3). Where grasses had not regrown to near pre-grazing levels, the pasture was rested longer. This was particularly important during the severe drought of 2002 when central Alberta experienced the worst single year drought on record (see Table 4.2).

The size of the sub-pastures used for the rotational grazing treatments varied among sites, as did the number of cattle present (Table 4.1), although rotational paddock sizes were kept relatively consistent within sites. The actual length of each grazing period in the rotational treatments on each site depended primarily on the condition and growth stage of the sward (both grass and CT), and the number of cattle available for grazing. Grazing periods were also affected by the date of initial livestock entry in spring by the landowner. Cattle utilized the continuous pasture at all times other than the few days they were placed into the smaller sub-pastures (for a maximum of 7 days total per SD/HILF rotation). The grazing treatments applied were approximately as follows:

1] Continuous – herbage grazed season-long with livestock access unrestricted to all portions of the pasture.

2] SD –herbage grazed to an average height of 15-cm (~50% utilization) in 2-3 days, but grazed relatively often, every 4-6 weeks.

3] HILF –herbage grazed to an average height of 2-cm (~80% utilization) and rested for about eight weeks before re-grazed.

The HILF system generally involved two grazing periods per growing season, while the SD treatment had 3-4 grazing periods, although the drought conditions of 2002 dictated less frequent grazing. Specific entry and exit dates for each treatment and year are provided in Table 4.3. Cattle in each paddock had unlimited access to water. During each grazing period, stocking rates (SR) were recorded for each paddock in order to track the total accumulated year-long SR in each grazing treatment at every site (Table 4.3).

To fully interpret the affect of each grazing treatment on CT abundance, we quantified actual forage utilization within each treatment. This was particularly important because SR was not constant among treatments between sites, nor treatments within sites. Utilization was measured to assess how much non-CT herbage had been removed during each grazing period. Within the continuous treatment, utilization measurements were taken in conjunction with measurements in the rotational sub-pastures. As a result, while the implementation of grazing treatments (i.e. put and take, or starting and stopping criteria) in the field were somewhat ‘rule of thumb’, the quantification of actual herbage removal allowed for more robust interpretation of the impact of each treatment on CT abundance.

4.2.3 Utilization

Utilization levels of non-CT herbage were measured at each grazing period, starting in 2001. Two portable, 1.5- x 1.5-m livestock exclusion cages were randomly placed within each grazing treatment at each site to assess utilization using the paired-plot method (Bonham 1989). Three cages per treatment were used at site three as this site was larger than the others (Table 4.1). After grazing was applied to each sub-pasture in each period, 0.25-m^2 quadrats (i.e. 50- x 50-cm) inside the cage were clipped to ground level to determine CT and non-CT herbage biomass without exposure to cattle grazing. At the same time, herbage and CT biomass 1-m outside the cages (and following exposure to grazing) was harvested to quantify the remaining biomass. Within each rotational sub-pasture, exclusion cages were moved to new randomized areas prior to each successive grazing period. Because of the relatively high stocking density and associated intensive grazing pressure within the HILF treatment, several cages used to determine utilization were initially knocked over. To protect against data loss, 2 or 3 quadrats (2 at all sites except site 3, where 3 were used) were clipped in 2002 prior to cattle entering sub-pastures in the event cages were knocked over, with pre-grazing herbage biomass levels used to estimate ungrazed biomass if cages were lost. After cattle were removed from sub-pastures, adjacent paired quadrats were harvested to determine post-grazing biomass. This method was used in conjunction with the paired-plot method described above, as a back-up for if and when cages were lost. The loss in exclusion cages occurred frequently, especially in the HILF treatment, as grazing pressure was high. Also in 2002, when drought conditions were extreme, it was difficult to keep the cattle from removing the cages as there was a lack of forage for them to access. However, the difference between the measurement methods was minimal, with However, the difference between the measurement methods was minimal, with mean measured grass utilization levels using the caged method and the pre and post-grazing method, averaging 73% (+/-2.1%) and 47% (+/-4.2%) for the HILF and SD treatments, respectively across the four sites. Because of the similarity in use between the two methods, we are confident that the data from each method are comparable. Utilization estimates in the continuous treatments were sampled once, at the end of the growing season. Biomass inside exclusion cages protected from grazing during the entire growing season were also harvested at this time, as well as within paired plots outside the exclusion cages that were exposed to season-long grazing. This may serve to over-estimate utilization in the continuous treatment, as previous studies show that deferred defoliation will maximize grass production over continuous grazing (Chapter 3, this volume).

All harvested samples were sorted to grass, forb and CT components, oven-dried at 50°C for 72 hr and weighed. The difference between caged and uncaged values (or pre- and post-grazing values where applicable) provided an estimate of utilization of each component during each grazing period.

4.2.4 Vegetation Responses to Grazing Systems

All field sampling to assess the impact of the three grazing systems on pasture vegetation was conducted along two permanently marked, 10-m transects within each grazing treatment at each site. Initial CT stem counts were taken before cattle entry into the sub-pastures and the continuously grazed pasture within five, 0.5-m^2 permanent quadrats along each transect (n=10/treatment). In 2000, only two sites had been established as a preliminary assessment of the feasibility of CT control with grazing. Thus, CT density was recorded only three times during that year; once at the beginning of the grazing season before any treatments had been imposed, once in the middle of the season after two SD grazing periods and one HILF grazing period had occurred, and a final sampling at the end of the growing season after all treatments had ended.

From 2001 to 2002, initial and year-end measurements were repeated within permanent quadrats at all four study sites. However, the frequency of repeated sampling also increased during each growing season in order to track the cumulative influence of each grazing period within each grazing treatment on CT stem density. Measurements of CT density were taken prior to and after each grazing period within the rotational treatments. Concurrent measurements were taken along the transects within the adjacent continuous pasture at each site. Additionally, visual assessments of the proportion (%) of CT defoliated or trampled (data not presented as trampling did not seem to have a significant effect), along with CT maximum height and average growth stage were assessed prior to and after each grazing period within all permanent quadrats in 2001 and 2002. Height of the tallest CT stem in each permanent quadrat was measured, and every plant within the sampled quadrats was rated for growth stage (rosette, bolt, flowering, or fluff) enabling the proportion of CT shoots in each stage to be calculated for all grazing treatments. All pastures were left undisturbed over winter, and the same treatments applied for a second, and where applicable, third year (for a site map, see Appendix One).

In order to evaluate the actual pasture sward response to grazing treatments, additional randomly placed exclusion cages (n=2 at sites 1, 2, and 4, and n=3 at site 3) were used to assess maximum above ground net primary production (ANPP) of herbage. Exclusion cages were placed in each treatment in the second and third years of successive treatment, and were allowed to grow unimpeded by cattle during the growing season in order to assess the effect of the grazing regime imposed during the previous year(s). At the end of the growing season (mid-August), all plant biomass was harvested from 0.25-m^2 quadrats within these cages to ground level, separated into grass and non-CT forb components, dried and weighed. CT biomass was not harvested.

The rotational grazing treatments ended at all four sites in the spring of 2003. However, in order to test for any residual effects of the previous 2-3 years of treatment, three exclusion cages were randomly placed on each treatment (continuous, SD, and HILF) at three sites (site 3 was excluded because cattle had already accessed the area) at the beginning of the growing season before cattle were introduced. During 2003, all pastures reverted back to the original continuous grazing regime they were under prior to initiation of the study. This enabled an evaluation of whether any observed treatment effects (i.e. potential change in CT) would carry over into subsequent years. In August of 2003, non-CT biomass in each cage was harvested and processed the same as in previous years. Finally, CT density was recorded for each treatment pasture along the original permanent transects at the end of the growing season in 2003 in order to track any recovery of CT shoots with cessation of the rotational grazing treatments.

4.2.5 CT Forage Quality

During 2002, the forage quality of CT was assessed throughout the growing season within each grazing treatment. Two procedures were used to assess this parameter. First, 10 CT stems were selected from each continuously grazed pasture at each of four times during the growing season: (1) the first week in June, (2) the first week in July, (3) the first week in August, and (4) the first week in September. At the appropriate sampling time (i.e. rosette at June 1, bolt at July 1, early flower (bud) at August 1, and seed dispersal (fluff) at September 1), 10 CT stems representative of each of four predominant phenological growth stages were harvested within each pasture. Plants were randomly harvested and bulked for processing to growth stage for analysis. Plants were weighed fresh, dried, and reweighed to determine fresh water content. Samples were then ground through a 1mm Wiley mill and tested for nitrogen (N) and acid detergent fiber (ADF). Total nitrogen content was determined using a Leco nitrogen analyzer (Leco Corporation 1992). Acid detergent fiber (ADF) of CT was evaluated using the filter bag technique (Komarek 1993).

The second set of CT forage quality data examined inherent differences in the quality of CT plants between actual paddocks containing different grazing treatments during the summer of 2002. To evaluate these differences, 10 CT plants were randomly selected from each rotational sub-pasture and continuous pasture at each of the four times previously described, regardless of phenological staging. As this data was to determine the differences in quality between treatments (and not between plant stages), all stages of plant growth could have been present at one time (more specifically, this occurred at the August and September sampling periods). The 10 plants were then bulked, and subjected to the same processing and quality determination outlined for the previous samples.

4.2.6 Data Analysis

This study was designed to quantify CT responses to three different grazing systems. CT responses included stem density, maximum height, stage of development (i.e. proportion flowering), as well as CT forage quality, over several years of consecutive measurements. Although CT staging data were collected for 4 different phenological growth stages, these data were simplified for statistical analysis into the proportion of CT stems flowering (i.e. at bud or seed dispersal stages). Additionally, utilization measurements of grass and forb components were made. This analysis was done across 4 sites in 2001 and 2002, as utilization data for the grass and forb components were not collected in 2000. All data were initially checked for normality using the Kolmogorov-Smirnov test ($p>0.05$) prior to analysis with a split-split-block analysis of variance (ANOVA). Although most data were found to be normal, CT nitrogen content was not normal (KS test $p=0.02$). Normality of this parameter was obtained using a log 10 transformation prior to analysis. Covariate testing was also done for all four sites using the baseline CT data collected in 2000 for sites 1 and 2, and the

2001 data for sites 3 and 4. Covariate testing determined whether the differences in starting CT density affected subsequent characteristics of CT.

Initial data analysis incorporated year to assess differences in responses between the first and second year of treatment effects. Emphasis in this analysis was placed on significant year, year by grazing, and year by grazing by site effects. CT density, height and growth stage (i.e. proportion flowering), as well as grass and forb utilization, were subsequently analyzed separately in year one and year two to evaluate the temporal pattern of vegetation responses to the imposed treatments. Emphasis during this analysis was placed on grazing treatment, and site by grazing effects. Analysis was also conducted on CT height and growth stage, together with grass and forb utilization from all years in order to observe year effects. CT density was analyzed from across three years on sites 1 and 2, and across two years on sites 3 and 4 to evaluate year effects.

All data were analyzed using both Proc GLM and Proc MIXED (SAS Institute Inc. 1988). Proc MIXED was initially used because data were unbalanced (two vs. three years) and Proc MIXED is better able to handle unbalanced data. However, initial analysis with this procedure indicated there were no differences in analysis outputs from either method. Moreover, because interactions among main effects can be more directly isolated from the analysis conducted through Proc GLM rather than Proc MIXED, Proc GLM was used to analyze the data. Post-hoc mean comparisons were conducted for all significant grazing effects and higher level interactions incorporating grazing, based on F-test results where $p \leq 0.05$. However, a more conservative $p \leq 0.10$ was used for the CT quality tests due to the limited sample sizes available for these tests (n=2 per paddock).

Mean comparisons were completed using Tukey's method ($p \leq 0.05$). All mean analysis was conducted using LS means due to the unbalanced design of the experiment.

4.3 Results

4.3.1 Pasture Utilization

Due to the large paddock sizes associated with continuous grazing, these treatments had the lowest overall stocking rate (SR, animal number/unit area/unit time) of all treatments, which ranged from 1.3 to 3.8 $AUM.ha^{-1}.yr^{-1}$. In comparison, the SD treatments had individual SRs within each grazing period ranging from 1.0 to 2.9 $AUM.ha^{-1}$. When totaled over the entire season to obtain an accumulated SR, these levels ranged from 3.1 to 7.7 $AUM.ha^{-1}\cdot yr^{-1}$, approximately double that found within the continuous treatments. Finally, individual SRs in the grazing periods of the HILF treatment were greater yet, ranging from 1.9 to 4.8 $AUM.ha^{-1}$, and totaling 2.1 to 8.9 $AUM.ha^{-1}.yr^{-1}$ (Table 4.3).

During 2001 and 2002, there were no significant differences ($P>0.05$) in the relative utilization (%) of forbs (Table 4.4), although only site effects could be assessed as only one site had forbs present. However, grass utilization (%) varied among grazing treatments ($P \leq 0.05$). In 2001 and 2002, grass utilization was greater ($P \leq 0.05$) within the continuous treatment than either of the rotational treatments (Table 4.5), while the SD grazing treatment had lower ($P \leq 0.05$) grass utilization than the HILF treatment. The lack of a significant site interaction indicated this pattern was consistent across sites (Table 4.5).

Actual levels of herbage (excluding CT) removal within each of the grazing treatments followed a pattern similar to relative utilization (Table 4.6), being greatest within the continuous treatment and least within the SD. Levels of forb removal tended to follow a pattern opposite that of grass biomass, being greatest within the HILF treatment, although only site four had a large enough forb component to effectively assess utilization. Some CT biomass was collected under the exclusion cages, and could be used to get an indication of CT biomass actually removed by cattle in each treatment. However, CT biomass removal data were not analyzed statistically as CT plants often grow in distinct patches, so CT was not always present in all the places the exclusion cages were placed, and therefore sampling may have been inadequate. When the amount of CT biomass removed was calculated for each grazing treatment, total utilization including CT tended to be greatest within the HILF treatment, followed by the continuous and SD treatments, respectively (Table 4.6) (see Appendix 3 for photos).

4.3.2 Thistle Density

There were no significant covariate effects of initial CT density on subsequent measures of CT density with grazing in the first, second or third year of treatment (data not shown). CT density did show significant ($P \leq 0.05$) grazing and site by grazing effects (Table 4.7). Additionally, CT density displayed a significant ($P \leq 0.05$) year by grazing by site effect (Table 4.7), suggesting grazing and site effects varied with the year of accumulated treatment.

In the first year grazing treatments were conducted, CT density was generally greater ($P \leq 0.05$) in the continuous treatment than the HILF treatment (Table 4.8). The

SD treatment was generally similar to the continuous treatment, with the exception of site 3, where there was no difference ($P \leq 0.05$) between the HILF and SD treatments. At site 4, no significant differences were evident among any of the grazing treatments, although CT density followed a similar trend as described above.

In the second consecutive year treatments were conducted, overall effects among sites indicated all three grazing treatments differed ($P \leq 0.05$) from one another, with the continuous and HILF treatments having more and less CT stems, respectively, relative to the SD treatment (Table 4.8). While full separation of treatments occurred at sites 1 and 4, treatments at sites 2 and 3 were less differentiated. At site 2, only the HILF treatment was lower ($P \leq 0.05$) than the continuous treatment, while at site 3, both the SD and HILF treatments were lower ($P \leq 0.05$) than the continuous (Table 4.8).

At both the sites where a third year of grazing was conducted, the HILF treatment had less ($P \leq 0.05$) CT than the other treatments (Table 4.8) (see Appendix 3 for photos).

4.3.3 Thistle Flowering and Height

Flowering CT stems included those in the bud and fluff (i.e. seed dispersal) stages. Initial analysis indicated there were no significant ($P \leq 0.05$) year effects for growth stage (data not shown). Within each year that growth staging was assessed, the amount of flowering CT was significantly ($P \leq 0.05$) affected by both grazing and site by grazing effects (Table 4.9). The HILF treatment was successful in reducing the proportion of flowering CT stems in both the first and second years relative to the continuous grazing treatment (Table 4.10). In contrast, the SD treatment resulted in an intermediate level of flowering in both years, although it remained statistically similar

($P>0.05$) to the continuous treatment in the second year (Table 4.10). A more detailed breakdown of the growth staging of CT plants in each grazing treatment during the first and second year of monitoring are provided in Figure 4.1. These data clearly show the effectiveness of the HILF treatment in limiting CT development beyond the bolting stage, while the majority of plants in both the continuous and SD treatments were able to progress through to flowering. During the entire study, only 3 CT plants monitored in the HILF treatment reached the bud stage, and they were destroyed by frost prior to producing seed.

Patterns in site-based variation in the flowering data were similar to the CT density data, with the HILF treatment consistently resulting in less ($P\leq0.05$) CT flower production than the continuous treatment in all years at all sites (Table 4.10). However, the SD treatment exhibited considerable variation in its effectiveness to reduce flowering. For example, during the first year, the SD treatment resulted in similar flower production to the HILF at site 3, similar flowering to the continuous treatment at site 4, but an intermediate level in between the other treatments at sites 1 and 2 (Table 4.10). In the second year, the SD treatment was able to reduce CT flowering ($P\leq0.05$) below the continuous treatment only at sites 3 and 4.

When analyzed across years, CT height had significant ($P\leq0.05$) grazing, site by grazing, year by grazing, year by site, and year by grazing by site effects (Table 4.7).

Examination of the specific CT height data among sites, grazing treatments, and years indicated that the HILF treatment resulted in the lowest CT height (Table 4.10). Moreover, this treatment had shorter CT ($P\leq0.05$) than both the continuous and SD treatments, in both years, and across all sites. The site-based interactions evident for CT height resulted from the inconsistent ability of the SD treatment to reduce CT height relative to the continuous treatment: CT heights within the SD treatment remained shorter at all times and sites, except site 2 in both years, and site 4 in year two (Table 4.10).

4.3.4 Thistle Quality

Both ADF and water content exhibited a significant ($P \leq 0.05$) grazing effect (Table 4.11). ADF also had a significant ($P \leq 0.05$) site effect, while water content had a site by grazing effect, a sampling time (ST) effect, and a ST by site interaction. Nitrogen (N) content only had a significant ($P \leq 0.05$) ST effect (Table 4.12). Examination of these data by site indicated that no differences in nitrogen content existed at sites 3 and 4. At site 1, the SD treatment tended to have greater N levels ($P \leq 0.05$) than either of the other treatments, and at site 2, the HILF treatment had CT with greater N levels than the continuous treatment (Table 4.13). When examining site effects, CT plants at site 1 had a greater ADF content than CT plants at site three (data not presented). Additionally, ADF content was significantly ($P \leq 0.05$) greater in the continuous treatment as the CT plants were more advanced, and lowest in the HILF treatment (the youngest CT plants). This trend occurred at all sites (Table 4.13). Water content was generally significantly ($P \leq 0.05$) greater in the HILF treatments than all others. Differences in fresh water content only occurred at sites 3 and 4, where CT plants in the SD treatment were slightly greater than both the HILF and continuous treatment (Table 4.13).

Additionally, the quality variables of N and fresh moisture content demonstrated significant responses to growth stage ($P \leq 0.05$) (Table 4.12). ADF had no significant growth stage effects. Forage quality was generally greater ($P \leq 0.05$), as exhibited by greater N and moisture, but less ADF, in earlier stages of growth, particularly the rosette stage (Table 14). The greatest differences among progressive developmental growth stages within the CT were evident within N levels (Table 4.14).

N concentrations were significantly ($P \leq 0.05$) greater at the June 1st sampling time, followed by the August 1st, July 1st and September 1st sampling times, respectively (Table 4.14). This trend only differed at site 4, where the July 1st sampling time had slightly greater N content than the August 1st sampling (data not presented). Water content was significantly ($P \leq 0.05$) greater at the June 1 sampling time than all other treatments, followed by July 1st, August 1st, and September 1st samplings, respectively (Table 4.14). This only differed at site 1, where the July 1st sampling had the lowest water content, and at site 4, where the August 1st sampling had greater water than the July 1st sampling time (data not presented).

4.3.5 Post-Treatment Grass Production and Thistle Density

Grass production and CT density were measured in 2003, one year after grazing treatments had ended. CT density displayed significant ($P \leq 0.05$) grazing and site by grazing effects, while grass production displayed a significant ($P \leq 0.05$) site and site by grazing effect (Table 4.15).

Residual CT density continued to exhibit the same trend among grazing treatments observed previously, with the SD treatment having fewer ($P \leq 0.05$) CT than the continuous treatment, but more CT stems ($P \leq 0.05$) than the HILF treatment (Table 4.16). This trend only differed at site 3, were there was no significant ($P > 0.05$)

difference between the SD and HILF treatments. Notably, no CT stems were found on the HILF treatment at any of the 3 sites.

Grass production also displayed major differences among grazing treatments one year after treatments were completed. Grass production was significantly ($P \leq 0.05$) lower in the continuously grazed area than within either of the rotational regimes (Table 4.16), by 39% and 64% relative to the SD and HILF treatments, respectively. The site-based interaction in grass production was due to inconsistencies in differences among grazing treatments at the 3 sites examined (Table 4.16). For example, at site 3, the HILF system produced more ($P \leq 0.05$) grass than the SD treatment only, while at site 1, only the SD treatment out-yielded ($P \leq 0.05$) the continuously grazed treatment area.

4.4 Discussion

4.4.1 Continuous Grazing

Continuous grazing resulted in the tallest and greatest density of CT at the end of the study, indicating this grazing system appeared to favor the growth and development of this noxious weed. Abundant levels of CT within the continuous grazing system likely result from the low palatability of CT stems and resulting lack of disturbance to these plants. Although overall grass relative utilization reached levels as high as 88%, the low stocking density of cattle in continuously grazed pastures would allow cattle to graze with maximum selectivity (Heitschmidt and Stuth 1991). Maximum selectivity would allow cattle to avoid thick CT patches and even individual plants, and forage instead on pasture microsites dominated by palatable herbs. Moreover, the constant accessibility of cattle to the entire pasture would allow animals to repeatedly regraze grasses and grass-dominated patches. Heavily utilized areas, in turn, have previously been documented to facilitate increases in CT (Chapter 3, this volume), likely due to a reduction in the vigor of grasses and the increased resources (light, water, nutrients) available to CT. Reduced vigor of grasses would lead to slower growth and lower total grass production as well, which would then result in relatively greater use of grasses as cattle are forced to graze them more closely.

Continuous grazing also allowed CT stems to consistently reach advanced stages of growth in all years of the study, with the majority of stems able to flower and produce seed, thereby presenting a risk of weed spread. Advanced staging of CT plants also results in lower quality of CT as potential forage, with lower N and greater ADF levels. These characteristics, in turn, would reduce the palatability of CT relative to young, rapidly re-growing grasses, further reinforcing the avoidance of CT and selection of other herbs, thereby reducing the latter's vigor. We did not directly test in this experiement whether cattle preferred to eat the flowers of CT over other parts.

4.4.2 HILF Grazing

Pastures grazed with the HILF system had the opposite impact on CT abundance compared to the continuous grazing system, resulting in the shortest CT stems and the lowest CT stem density. There are two potential mechanisms that may be responsible for the reduction in CT. Previous research has shown that infrequent, but intense, selective defoliation of adjacent non-CT herbs has the potential to reduce CT abundance (Chapter 3, this volume). Because the defoliation treatments used in that study did not impact CT directly, the CT decline was attributed exclusively to alteration of the competitive balance between CT and adjacent herbaceous species. More specifically, greater overall forage regrowth under HILF defoliation was thought to maximize season-long competition against CT for water and nutrients.

In the current study, cattle were used as the defoliation agent. Thus, in addition to the competitive shift in favor of non-CT herbs, CT plants in grazed pastures would have been affected directly by cattle, either through defoliation or trampling. The HILF grazing system used here employed a much greater stocking density (no. animals per unit area) relative to the continuous grazing treatment due to the localized area in which cattle were briefly confined. A high stocking density would increase the chance that CT plants would be trampled by cattle as they socialize and move about the paddock looking for forage. Indeed, CT stems were sometimes observed to be knocked down to the ground, broken off, or at a minimum, stripped of many leaves and branches. Additionally, this trampling effect may have damaged CT plants allowing for disease entry and accelerating CT mortality. However, the vast majority of CT plants were totally defoliated, stem and all.

Previous research has shown that animal grazing preferences change with both stocking density and grazing pressure (Heitschmidt and Stuth 1991), the latter of which is regulated by forage depletion (i.e. ratio of forage demand to forage utilization). Total utilization within the HILF treatment was 72%, considered moderate to high based on the frequently held notion of “take half, leave half”. Within the HILF grazing treatment, intense competition for available forage among cattle during a short period of time appeared to force cattle to utilize much of the CT biomass. This trend was exemplified by the high overall level of total herb (including CT) biomass utilization within the HILF paddocks, which was greater than in the other treatments. Moreover, of the total biomass removed by cattle, approximately 40% consisted of CT. Indeed, visible signs of CT use in each pasture became evident late in each HILF grazing period (i.e. in the last day or so), suggesting cattle initially avoided portions of the pasture where CT was abundant, only to move into those areas as preferred areas were depleted of forage. In comparison, very little CT biomass was removed in the continuous grazing treatment (<1% of total biomass removed was CT), and therefore this plant did not contribute to supporting cattle production under continuous grazing. In contrast, the HILF grazing system was able to make effective use of CT as a source of forage.

Direct cattle use of CT may have been greater within the HILF grazing treatment due to several mechanisms. First, cattle may have consumed CT incidentally to foraging on desirable species found in close proximity to the weed. This is the primary way in which CT was impacted. Second, high animal densities typically resulted in vegetation trampling. However, while grasses were often flattened close to the ground, sharply reducing their accessibility to grazing cattle, CT plants often remained standing due to their stronger stems. Thus, cattle may have switched to foraging on CT because of its greater accessibility, and to maintain foraging efficiency through maintaining adequate bite size as the grass no longer presented enough biomass. Notably, the flattened condition of many of the grasses in the HILF treatment may have limited the level of forage utilization from being even greater.

Uniform defoliation of all vegetation in a pasture typically shifts the competitive balance among species in favor of those with rapid regrowth characteristics. In our pastures, forage grasses were those that were highly tolerant of grazing, with rapid regrowth from axillary buds (tillers) and intercalary meristems on remaining leaves, as well as below-ground rhizomes. Combined with the slow regrowth of CT from below-ground, this process was likely responsible for much of the shift in competitive advantage from CT to perennial grasses, and therefore helps account for the marked reduction in CT stems. Rapidly regrowing grasses would not only reduce the amount of water and nutrients available for CT, but also rapidly develop a canopy that would reduce available light. Other research has shown that CT is susceptible to low light levels, which reduces their growth potential (Jordan 1996; Pester et al. 1996; Donald 1990; Pook 1983; Medd and Lovett 1978).

The use of high stocking densities led to brief, intensive utilization within the HILF paddocks, in which forage utilization reached levels considered high by many grazing managers (i.e. >>50%). Although this level of utilization appeared slightly lower than that of the continuous treatment, because HILF grazing occurred in more than one grazing period per year, overall levels of actual biomass removal in the HILF grazing treatment were greater. This trend is further supported by the season-long SRs recorded for the HILF treatment, which were approximately double that of the continuous treatment. Although this high utilization might appear to suggest that HILF grazing is no more or even less sustainable than continuous grazing, this was not supported in our study. The greater stocking rates are not reflective of greater short-term exploitation of grass biomass, but instead are the result of enhanced grass growth due to the long recovery time following each grazing period. These results suggest variation in stocking rate alone was not reflective of the potential impact on pasture vegetation, particularly when confounded by the use of different grazing treatments. Many previous studies that have tested different grazing systems have confounded grazing system (i.e. the timing and frequency of use) with the use of different stocking rates (Willms et al. 1985, Walker and Heitschmidt 1986), making it impossible to clearly distinguish between the individual importance of variable SRs and grazing systems in altering animal performance and rangeland sustainability. Our results indicate that greater stocking rates may indeed be justified when using an HILF grazing system in the Aspen Parkland of central Alberta, as this system simultaneously led to greater pasture use, reduced CT, and greater forage production at the end of the trial. More specifically, high levels of utilization or stocking rates appear sustainable in this system, provided grazing occurs in a short period of time and is followed by a long recovery period.

The HILF grazing system was also highly effective in altering CT development. The vast majority of CT stems in this treatment were maintained in the rosette stage, accounting for the low CT heights consistently found, with little development to flowering. This finding was attributed to the ability of the HILF system to force cattle to consistently and uniformly defoliate and/or damage CT vegetative stems. Moreover, because CT is a forb with an elevated meristem, heavy damage to the above-ground material was able to terminate shoot development and avert flowering and seed production. Instead, CT were often forced to regrow from root buds located below the ground surface, a process that can result in prolific new shoot production (Grekul 2003; Amor and Harris 1977), but is also quite slow to occur. In this study, HILF grazing periods were observed to be followed by extensive regrowth of CT stems, which were unable to develop beyond the bolting stage before being regrazed and damaged up to 8 weeks later. Repeated over time, this process likely had the effect of depleting root carbohydrates within the remaining CT population, similar to that evident under repeated mowing or tillage (Donald 1990; Hodgson 1958,1968). Repeated mowing has been shown elsewhere to be effective in controlling CT, provided it is done several times a year over several years (Wilson and Kachman 1999; Hartley and James 1979; Amor and Harris 1977; Schreiber 1967; Thrasher et al. 1963; Derscheid et al. 1961; McKay et al. 1959; Welton et al. 1929; Detmers 1927). By the end of the present study, little CT regrowth was evident in HILF treatments, even after a return to continuous grazing in 2003, indicating the reduction in CT shoot production was more than cosmetic in nature, and likely reflected root mortality.

Maintaining CT in a young stage of growth had the added benefit of maintaining these shoots in a more palatable and nutritious condition. Rosette plants were typically greater in N and lower in ADF, indicating they had greater nutritive value to cattle. Similarly, these plants also had greater moisture content. Coupled with the lower lignin levels typically associated with younger vegetative growth (Sultan-Singh et al. 2003), these plants would be more palatable to grazing cattle, and would have a greater chance of being eaten. As CT stems age, they tend to become more lignified, and prickly, characteristics that would undoubtedly affect an animals likelihood to forage on them.

4.4.3 Short Duration Grazing

While the SD treatment sometimes resulted in lower CT density than the continuous system, it was seldom significantly different. Stocking rate was also higher in the SD pastures than the continuous (nearly double), more similar to that in the HILF system, but these results suggest grazing pressure was not high enough in this treatment to induce cattle to consume significant amounts of CT. Given that total utilization in the SD treatment averaged around 53%, grazing pressure was not high enough to force animals to utilize CT. This was further reinforced by the lower amount of CT used by the cattle in the SD treatment relative to the HILF. Cattle in the HILF system added 40% of standing CT to their total diet, while less than 10% of total forage intake (averaged for sites 1, 2 and 4) in the SD pasture consisted of CT. Therefore, observed reductions in CT were likely the result of physical damage to the weed (i.e. trampling) and associated competitive shifts away from CT in favour of rapidly regrowing forage grasses. While this treatment allowed for the grass community to stay competitive because only half of the plant material was defoliated at a time, leaving more plant biomass for photosynthesis and regrowth, and frequently, so that plants should have been kept in a state of regrowth, this did not appear to be enough of an advantage to effectively compete against tall and vigorous CT. The other possible advantage of the SD treatment over the continuous is that the temporary high stocking densities may have forced animals to at least enter those heavily infested CT patches that they would otherwise avoid in the continuous treatment. Because of this, some CT damage occurred due to trampling, and in some cases the tops or leaves of the CT might 'accidentally' be removed during foraging. This activity would at least break up dense CT patches, and perhaps allow for some grass recovery in these areas. However, as observed in this study and in the associated clipping trial (Chapter 3, this volume), it appears that the perennial pasture grass species in this area are well-adapted to intense grazing, and the length of the rest period is key in maintaining their vigor. Overall, it seems that the SD treatment may not be as advantageous to enhancing grass growth or maximizing grass production as often thought (Paige and Whitman 1987; Belsky 1986; Hart and Balla 1982; McNaughton 1979; Dyer and Bokhari 1976) with less impact on associated weeds. Rather, this system is likely most advantageous in maximizing forage availability and providing consistent quality throughout the growing season.

In most cases there was no difference in CT height between the continuous and SD treatments. It is not surprising that CT height was not altered in these treatments, as cattle would avoid defoliating these plants at a conservative grazing pressure. Similarly, the stage of plants observed in the SD treatment resembled those found in the continuous more than the HILF treatment. In the first year, the SD grazing treatment had fewer flowering plants than in the continuous. However, in the second year, there was no significant difference. Flowering may have been somewhat affected by this treatment due to trampling of CT plants and topping of flower buds by cattle. However, because there was limited disturbance overall to these CT plants, they were able to progress through their growth cycle primarily unchecked, resulting in increased flowering.

Quality was not affected by the SD treatment as it was by the HILF. Because the stage of development of CT plants was not altered, it is unlikely that the overall quality of CT available to cattle would change. However, the SD treatment was able to alter N and water content so that there was no significant difference between the bolt, bud and seed disperal stages (the continuous had a drop in N and water content at the seed dispersal stage). This extension of favorable CT quality using rotational systems is advantageous to provide better forage for grazing animals. However, the SD treatment was not able to keep CT plants at the youngest (rosette) and highest quality stage as did the HILF treatment.

In 2003, when grazing treatments had ended, there was no difference in CT densities between the continuous and SD treatments, indicating that the SD grazing system did not effectively alter CT populations during the treatments but rather resulted in more rudimentary 'visual' decreases in the weed. Similarly, when grass production was analyzed after treatment ceased, the HILF treatment showed greater production than the SD treatment, indicating that the former allowed maximum grass regrowth, which captures the most production possible of all the systems. However, this was only true for sites 1 and 3. At site 2, the SD treatment had slightly greater production than the HILF treatment. This site was along a riparian area with higher water levels, and therefore greater growth potential may have favored more frequent grazing at a lower utilization level.

Site 3 was an exception to the trends found in the other three sites with respect to the SD treatment. At this site, the SD system exhibited the same level of control as the HILF treatment in all parameters. Even though utilization in this treatment was 51%, cattle added about 1800 $kg\cdot ha^{-1}$ of CT to their diet because they used nearly 100% of the CT (the average of the other SD sites was 10% CT use). Cattle at this site readily grazed CT in the rotational treatments regardless of high (HILF) or low (SD) grazing pressure, an observation not made at any other site. These cattle were of typical British – European cross origin, so it is unlikely that the breed of cattle influenced their selection. However, because these cattle behaved differently from most, it is possible that these animals may have already been conditioned to feed on CT. Other research shows that if animals are exposed to a plant that they are naturally adverse to early in life, they will continue to readily consume it as they age (Burritt et al. 2000). Similarly, if animals with an aversion to a plant see other animals consume that plant, they will sample it, and the adverse reaction will be extinguished (Ralphs and Provenza 1999). CT ecotypes are also known to have different characteristics in regards to the amount and length of spines as well as leaf epidermis characteristics (Moore 1975; Hunter and Smith 1972). It is unknown whether different ecotypes of CT were present at the four sites, but this may be a factor that influences cattle consumption. The 'voluntary' use of CT by cattle at site 3 was not observed to such an extent at any other site.

4.4.4 Management Implications

These results indicate that a HILF grazing system using cattle is capable of significantly reducing CT populations over a three year period with two grazing treatments per grazing season. This reduction in CT appears to continue even after the HILF treatment has ceased and a continuous grazing system has been implemented once again. This is not recommended, however, as re-establishment of the previous CT densities will likely occur with a return of the competitive shift in favor of the undefoliated or lightly defoliated weed. Many producers may be uncomfortable with the high utilization levels in the HILF system, and because the SD system may allow for a more consistant quality of grass and more possible grazing periods per season, one option is to use the HILF grazing system as a prescriptive treatment until CT populations have been reduced to an acceptable level, at which time the manager could switch to a SD system, where proper grazing management should keep CT populations low.

While the design of this study was to keep grazing periods similar in duration, real world conditions often prevented this. As mentioned previously, 2002 was an extremely dry year and all treatments had to be altered at all sites. After grazing, grass regrowth was often poor, or did not occur, likely because there was no moisture. As a result, in 2002, only one grazing period occurred in the HILF treatment on all sites, and only two SD grazing periods were imposed, half of that in previous years. Despite this, treatment differences similar to previous years were still observed, and we were able to use the data from 2002 successfully in the analysis.

The severe drought in 2002 may have affected the response observed in CT density as well. Shoot production can be inhibited when moisture is low (Dizenfog 1958), but underground root length can increase under drought conditions (Lauridson et al. 1983). CT is also able to inhibit root bud initiation under moisture stress. When moisture levels then rise (RH from 50 to 90%), stem height and shoot and root dry weights increase (Hunter et al. 1985). This allows CT plants to lay dormant until better conditions arrive, which could have given a false impression that CT populations were reduced in the HILF treatments. However, because data were collected after treatments had ceased in 2003, when rainfall was more normal, the same treatment responses were observed. Therefore, it is likely that the treatment effects observed from 2000 to 2002 were indicative of actual changes in CT populations, and not a CT response to drought.

There were also some definite differences between sites with respect to the responses among treatments. Sites 1 and 2 were the most similar in their response, even though they were very different sites, one being located on dry land and the other in a riparian area. Site 3 was atypical, as the cattle grazing this area readily consumed CT plants in both the SD and HILF treatments. These cattle apparently did not have to be forced to eat CT in the SD treatment, and often selected it over grass plants if more succulent leaves were removed from the grass. Therefore, at this site, CT density, height and growth stage were nearly identical for the HILF and SD treatments. Cattle did not consume the CT in the continuous pasture, however, likely because they had many other possible forage sites where there was no CT present, and therefore simply avoided those areas that contained the weed. Site 4 was also different from the others as it was the largest scale site. Over a hundred cows were used at this site, and the HILF and SD pastures were much larger than those built for the sites where only 15-30 cattle were used. It was difficult to keep these cattle in the HILF treatment because the electrical fencing charge was often not strong enough, and there were more cattle to test the fence. Additionally, because the cattle were not quite grazed at this site according to prescribed levels, only an 80% control of CT was achieved in this pasture. Despite these unique site differences, the treatments examined still exhibited a strong trend, and seem to indicate that the HILF system was able to reduce CT populations.

Animal behavior was altered due to the HILF treatment. The grazing time in the SD treatment remained relatively the same over three years, averaging 2.2, 2.0, and 2.3 days in year 1, year 2 and year 3 respectively. Conversely, the grazing time in the HILF treatment averaged 4.1, 3.0, and 3.0 days in year 1, year 2, and year 3, respectively (data not presented). The first HILF grazing period by cattle required on average one day longer for the animals to graze CT, as animals that likely had persistently avoided CT were not eager to consume CT plants, and had to be forced. However, after the initial graze of CT, cattle more readily grazed the plant in subsequent grazing periods, as they learned they could use it as forage. This change in animal behavior enhanced CT control in the HILF treatments as the cattle became trained CT defoliaters, thus reducing the time required in the treatment before initially sampling the CT. The most interesting animal behavior alteration was seen with the herd grazing site 2. This herd consisted of the same cattle for all three years (this occurred on no other site). In year three (2002), an extreme drought occurred. As a result, at the end of the season when the CT plants in the continuous pasture were examined, there were very few, if any, of the plants that had been present just weeks before. The cattle had selected the CT plants on their own, even in a continuous pasture situation. It seems that once they had learned that this plant was a possible source of forage (Ralphs and Provenza 1999), they fed on it when there was little grass or other more palatable species available to them, whereas in the previous year they left the CT plants, regardless of their hunger. This behavior shift could greatly enhance cattle as a biocontrol agent of CT if cattle are trained to use the weed as a source of forage. It is important to note that in this defoliation of CT in the continuous pasture, it was mostly the leaves and tops of stems that were removed from plants. In contrast, when the HILF treatment was imposed, the whole CT plant (stem and all) was removed. In the continuous system cattle left the main lignified part of the CT stem behind in most cases.

This research only looked at two possible rotational systems, one that had a utilization of approximately 50% (take half-leave half, or SD system), and one that had an 80% utilization level (HILF). There are infinite variations on rotational systems, depending on the length and intensity of use and rest time implemented, all of which have potential to alter the influence of cattle on weed and grass abundance. What this research indicates is that effective rotational systems require grazing that is intense enough to remove CT before grass is regrazed. Additionally, the rest time must be sufficient in length to allow for grass regrowth to an appropriate level, so that reductions in vigor do not occur in the desirable forage species. However this is accomplished, whether at a lower intensity (like site 3 with the SD system), or with different stocking rates and rest periods, these requirements need to be fulfilled in order to maintain a productive grass stand and reduce CT populations.

Unlike the clipping study (Chapter 3, this volume), fertilization was not a factor in the grazing system application. As was seen when macro-nutrient requirements were eliminated, pasture production and CT density and biomass reduction was optimized. By adding fertilizer to the HILF treatment, control of CT could have been further intensified, thus extending CT control into the years following the prescriptive HILF treatment. Additionally, reductions in CT in the SD treatments may increase if fertilizer is added, as the grass component of the pasture may be favoured, increasing its ability to compete with CT. Therefore, more research is needed to examine the effects of fertilizer on these grazing regimes and their ability to control CT.

All sites used in this study were located in the Parkland eco-region, one of the most productive regions in Alberta for pasture and rangeland due to its productive (i.e. Black Chernozemic) soils and relatively high growing season moisture. Moreover, the grass species used in pastures of this area are typically highly adapted to grazing, which are enhanced by adequate moisture levels during the growing season. Because of this regional localization of the research, it remains unknown how effective the HILF system will be in drier regions where grass species may not be as grazing adapted or able to handle periodic intensive defoliation. More research is needed in these areas to evaluate the possibility of employing the HILF treatment as a method of CT or other weed control in drier areas.

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Table 4.1. Location, size of the different grazing treatment pastures, number of cattle grazed at each of the different sites, and the initial thistle densities within each pasture.

Site		Treatment	Pasture Size (ha)	Number of Cattle	Initial CT Density (stems·m^{-2})
1	Wetaskiwin	Continuous	61.78	18	54.0
		SD	1.1	18	43.8
		HILF	1.1	18	50.4
2	Wetaskiwin	Continuous	32	20	21.2
		SD	0.9	20	12.0
		HILF	0.9	20	9.4
3	Rich Valley	Continuous	61.78	18	11.7
		SD	0.8	18	10.2
		HILF	0.8	18	11.0
4	Rimbey	Continuous	129.5	103	27.8
		SD	3.2	103	26.4
		HILF	3.2	103	23.6

Table 4. 2. Sites, landscape characteristics, and growing season precipitation for the four grazing sites.

Site	Slope/Aspect	Landform	Precipitation (May-Sept.; mm)				
			2000	2001	2002	30-yr Mean	30-yr High/Low
1	<2%/South	Rolling Moraine (Riparian Position)	364	286	196	393	531/170
2	Level/NA	Level Moraine (Dryland Position)	308	299	130	393	531/170
3	Level/NA	Floodplain	315	391	163	440	644/205
4	Gentle Slope /East	Rolling Moraine	395	274	191	485	730/337

Table 4.3. Dates of grazing within the different experimental pastures and sites over the three year study period, as well as stocking rates ($AUM \cdot ha^{-1}$) in parentheses for each grazing period.

Site	Treatment	2000	2001	2002
1	Continuous	June 1 - Sept 30 (2.0)	July 10 – Sept 30 (1.4)	June 1 - Sept 30 (2.0)
	SD	July 12 - July 13 (1.4)	July 28 - July 29 (1.4)	July 11 - July 13 (1.7)
		Aug 10 - Aug 11 (1.4)	Sept 12 – Sept 13 (1.0)	Sept 14 - Sept 15 (1.4)
		Aug 23 – Aug 24 (1.4)		
	Total SD SR	4.2[1]	3.4	3.1
	HILF	July 14 - July 17 (2.8)	July 25 - July 27 (2.1)	July 14 - July 16 (2.1)
		Aug 25 - Aug 27 (2.1)	Sept 14 – Sept 16 (1.9)	
	Total HILF SR	4.9	4.0	2.1
2	Continuous	June 15 - Sept 30 (3.1)	June 20 - Sept 30 (3.0)	July 10 - Sept 30 (2.4)
	SD	July 17- July 18 (1.9)	July 5 - July 6 (1.9)	July 30 - July 31 (1.9)
		Aug 11 - Aug 13 (2.9)	July 27 - July 28 (1.9)	Sept 3 - Sept 4 (1.4)
		Sept 8 - Sept 9 (1.9)	Aug 29 - Aug 30 (1.4)	
	Total SD SR	6.7	5.2	3.3
	HILF	July 13 - July 17 (3.8)	July 7 - July 9 (2.9)	Aug 1 - Aug 3 (2.9)
		Aug 23 - Aug 27 (4.3)	Aug 30 - Sept 1 (2.9)	
	Total HILF SR	8.1	5.8	2.9
3	Continuous		June 10 - Sept 30 (3.7)	June 10 - Sept 20 (2.6)
	SD		July 4 - July 5 (2.8)	June 27 - June 28 (2.8)
			Aug 7 - Aug 9 (2.8)	Sept 11 - Sept 12 (2.1)
			Sept 14 – Sept 15 (2.1)	
	Total SD SR		7.7	4.9
	HILF		July 6 - July 9 (4.1)	June 25 - June 27 (4.1)
			Aug 1 - Aug 5 (4.8)	
	Total HILF SR		8.9	4.1
4	Continuous		June 19 - Sept 30 (1.3)	June 15 - Sept 30 (1.3)
	SD		July 16 - July 17 (1.9)	July 9 - July 10 (1.9)
			Aug 10 - Aug 11 (1.9)	Sept 1 - Sept 2 (1.4)
			Sept 13 – Sept 14 (1.4)	
	Total SD SR		5.2	3.3
	HILF		July 17 - July 19 (2.9)	July 10 - July 12 (2.4)
			Sept 10 - Sept 13 (3.4)	
	Total HILF SR		6.3	2.4

[1] Total stocking rates for each grazing season of the rotational systems.

Table 4.4. ANOVA F-values from using Proc GLM for grass and forb relative utilization (%) showing significant effects for different grazing regimes across four sites and two years.

	df	Grass Use	Forb Use	Total Use
Site	3	3.06	1.30	6.38
Grazing (Grz)	2	15.47**	-	13.64**
Grz X Site	6	2.68	-	1.34

Year	1	0.01	-	2.25
Year X Site	3	0.54	-	1.11
Year X Grz	2	0.45	-	0.12

*, **, *** Indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.0001$, respectively.

Table 4.5. Grass and forb relative utilization for different grazing treatments at each of four sites during two years, and for all sites.

Site	Grazing	2001 Utilization (%)			2002 Utilization (%)		
	Treatment	Grass	Forb	Total	Grass	Forb	Total
1	Continuous	91	-	91	92	-	92
	SD	53	38	52	58	-	58
	HILF	78	98	81	84	-	84
2	Continuous	85	90	87	90	-	90
	SD	51	69	60	49	-	49
	HILF	73	8	72	84	-	84
3	Continuous	83	-	83	91	-	91
	SD	37	70	46	56	-	56
	HILF	69	-	69	68	-	68
4	Continuous	87	71	87	87	68	86
	SD	35	68	39	37	50	44
	HILF	64	66	65	59	59	59
All Sites	Continuous	86 a[1]	81		90 a	75	
	SD	44 c	61		50 c	44	
	HILF	71 b	56		73 b	52	
	SE	0.04	0.2		0.04	0.2	

[1] Within a column, grazing treatment means with different letters differ, $P \leq 0.05$.

Table 4.6. Mean grass and forb biomass utilization for different grazing regimes across four sites averaged across two years.

Grazing	Utilization ($kg \cdot ha^{-1}$)			
Treatment	Grass	Forb	Total Grass + Forb	Total with CT[2]
Continuous	2883 a[1]	-	2985 a	2993
SD	1371 b	40	1510 c	2157
HILF	2248 a	516	2320 b	3885
SE	160	-	200	-

[1] Within a column, grazing treatment means with different letters differ, $P \leq 0.05$.

[2] Total utilization estimate including CT was not analyzed statistically.

Table 4.7. ANOVA F-values from Proc GLM for CT density and height showing repeated measures effects for different grazing regimes across four sites and two years.

Source	df	Density ($\# \cdot m^{-2}$)	Height (cm)
Site	3	3.67	3.09
Grazing Trt (Grz)	2	14.59**	16.4**
Site X Grz	6	5.73**	160.26***

Year	1	0.00	1.21
Year X Grz	2	2.28	38.79***
Year X Site	3	5.86**	22.43***
Year X Grz X Site	6	3.4*	27.02***

*, **, *** Indicate significance at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.0001$, respectively.

Table 4.8. Thistle mean density and associated standard errors for different grazing treatments across four sites in each of two years, two sites in year three, and for all sites.

Site	Grazing Treatment	Year 1 Density (no.·m^{-2})	Year 1 SE	Year 2 Density (no.·m^{-2})	Year 2 SE	Year 3 Density (no.·m^{-2})	Year 3 SE
1	Continuous	44.8 a[1]	3.2	49.8 a	5.8	40.6 a	4.7
	SD	25 a	11.1	20.4 b	2.4	32 a	2.4
	HILF	15.2 b	1.4	0 c	0.0	0.6 b	0.2
2	Continuous	20.4 a	1.6	20.6 a	2.9	23.2 a	2.0
	SD	9.6 ab	0.8	16.8 a	5.6	16 a	2.0
	HILF	4.8 b	0.8	1.4 b	0.2	2.4 b	0.8
3	Continuous	44.4 a	13.2	35 a	6.6		
	SD	0.6 b	0.2	8.8 b	2.4		
	HILF	0.8 b	0.0	2.6 b	1.0		
4	Continuous	26.8 a	1.2	52.2 a	4.2		
	SD	23 a	0.6	28.6 b	3.8		
	HILF	17.4 a	0.6	17.2 c	4.4		
All Sites	Continuous	34.1 a		38.8 a		31.9 a	
	SD	19.6 ab		18.7 b		24 a	
	HILF	9.6 b		5.3 c		1.5 b	
	SE	6.2		6.2		9.72	

[1] Within a column and site, grazing treatment means with different letters differ, $P<0.05$.

Table 4.9. ANOVA F-values from Proc GLM for CT shoot densities in vegetative (rosette and bolt) and flower (bud and seed dispersal) growth stages showing significant effects for different grazing regimes across four sites in each of 2 years.

Year	Source	df	Vegetative	Flowering
First	Site	3	1.20	0.31
	Grazing	2	7.13**	43.21***
	Site X Grazing	6	27.88***	5.50**
Second	Site	3	1.05	4.52
	Grazing	2	10.52**	109.70***
	Site X Grazing	6	19.49***	3.44*

*, **, *** Indicate significance at $P\leq0.05$, $P\leq0.01$, and $P\leq0.0001$, respectively.

Table 4.10. Thistle mean stem height and proportion of CT stems flowering (% bud and seed dispersal taken at the end of the growing season) for different grazing treatments across each of four sites in two years, and all sites.

		Year 1			Year 2		
Site	Treatment	Height (cm)	SE	Flowering (%)	Height (cm)	SE	Flowering (%)
1	Continuous	151 a[1]	2.3	29 a	134 a	9.6	30 a
	SD	141 b	7.6	17 b	124 b	5.2	10 a
	HILF	2 c	1.5	0 c	0 c	0.0	0 b
2	Continuous	93 a	0.5	16 a	86 a	8.8	18 a
	SD	90 a	3.8	14 b	82 a	4.6	12 a
	HILF	4 b	1.2	0 c	6 b	2.5	0 b
3	Continuous	81 a	0.8	36 a	71 a	7.2	28 a
	SD	16 b	13.2	0 b	54 b	1.0	11 b
	HILF	5 c	1.2	0 b	4 c	2.7	0.4 b
4	Continuous	113 a	1.2	22 a	110 a	4.6	41 a
	SD	101 b	7.5	27 a	101 a	6.7	28 b
	HILF	22 c	1.5	0 b	67 b	4.2	3 c
SE				3.9			2.7
All Sites	Continuous	109 a		26 a	98 a		29 a
	SD	87 a		15 b	90 a		15 ab
	HILF	8 b		0 c	20 b		1 b
	SE	16.2		5.5	16.2		5.5

[1] Within a column and site, grazing treatment means with different letters indicate significant differences, P≤0.05.

Table 4.11. ANOVA F-values from Proc GLM for CT nitrogen content and ADF showing significant effects of different grazing treatments at four different sampling dates (June 1, July 1, August 1, and September 1) across four sites during 2002.

	df	Nitrogen Content (%)	ADF (%)	Water Content (%)
Site	3	1.14	14.00**	1.04
Grazing Trt (Grz)	2	2.16	3.63*	4.45*
Site X Grz	6	1.89	0.18	2.75*

Sampling Time (ST)	3	17.36****	1.17	24.61***
ST X Site	9	0.84	0.34	2.59*
ST X Grz	6	0.95	0.92	1.32

* Indicate significance at P≤0.05.

Table 4.12. ANOVA F-values from Proc GLM for CT nitrogen content and ADF showing significant effects of four different growth stages (rosette, bolt, bud and seed dispersal) across four sites during 2002.

	df	Nitrogen Content (%)	ADF (%)	Water Content (%)
Site	3	1.43	1.49	0.25
Growth Stage	3	19.18**	1.87	10.27**

*, **, ***,**** Indicate significance at P≤0.10, P≤0.05, P≤0.01, and P≤0.0001, respectively.

Table 4.13. Nitrogen, ADF and water content of CT for different grazing treatments across four sites sampled June 1, July 1, August 1 and September 1.

Site	Treatment	Nitrogen (%)	ADF (%)	Water (%)
1	Continuous	1.45 b[1]	0.20	0.77 b
	SD	2.01 a	0.19	0.72 b
	HILF	1.46 b	0.18	0.84 a
2	Continuous	1.73 b	0.19	0.80 a
	SD	2.06 ab	0.18	0.80 a
	HILF	2.25 a	0.18	0.85 a
3	Continuous	2.19 a	0.19	0.79 a
	SD	2.15 a	0.17	0.83 a
	HILF	2.18 a	0.16	0.81 a
4	Continuous	2.40 a	0.19	0.78 a
	SD	2.27 a	0.18	0.81 a
	HILF	2.00 a	0.17	0.80 a
SE		0.16	0.010	0.018

[1] Within a column and site, treatments with different letters differ, $P \leq 0.05$

Table 4.14. Nitrogen, ADF and water content of CT across four phenological stages of growth.

Sampling Time	Stage	Nitrogen (%)	ADF (%)	Water (%)
June	Rosette	2.98 a[1]	17 b	88.8 a
July	Bolt	1.54 bc	18 ab	74.7 b
August	Bud	1.60 b	19 ab	77.1 b
September	Seed Dis.	1.19 c	20 a	74.3 b
	SE	0.038	0.91	0.018

[1] Within a column, stages with different letters differ, $P<0.05$.

Table 4.15. ANOVA F-values from Proc GLM indicating CT density and grass production responses across three sites in 2003 to grazing treatments one year after treatments ceased.

	df	Thistle Density (#·m^{-2})	Grass Production (kg·ha^{-1})
Site	2	1.56	11.61*
Grazing	2	8.96*	2.66
Site X Grazing	4	16.65**	3.36*

*, ** Indicate significance at $P \leq 0.05$ and $P \leq 0.01$, respectively.

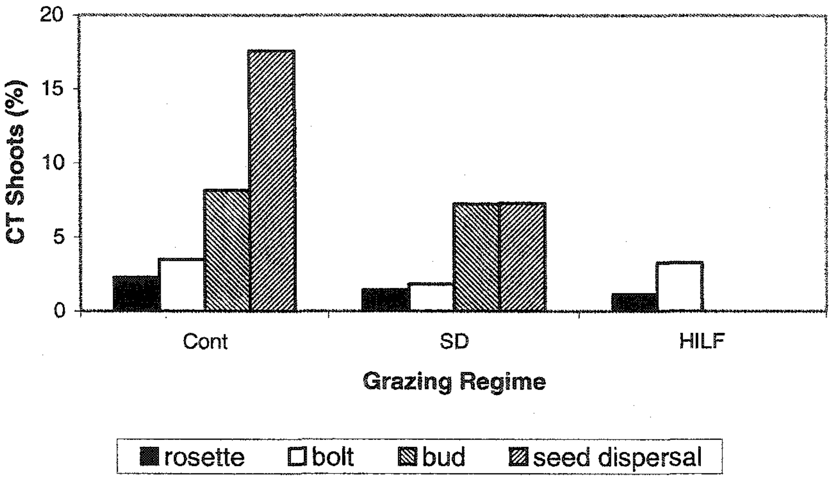
Table 4.16. Grass production and associated standard errors for different grazing regimes across three sites one year after cessation of treatments in 2003.

Site	Treatment	Thistle Density ($\#\cdot m^{-2}$)	Grass Production ($kg\cdot ha^{-1}$)
1	Continuous	22 a	4466 b[1]
	SD	17.9 b	6224 a
	HILF	0 c	5246 ab
2	Continuous	13.3 a	1529 b
	SD	9.9 a	1760 ab
	HILF	0 b	2706 a
3	Continuous	18.2 a	2721 c
	SD	0.5 b	4163 b
	HILF	0 b	5597 a
SE		1.5	417.7
All Sites	Continuous	17.8 a	2909 b
	SD	9.4 b	4049 a
	HILF	0 c	4516 a
SE		0.9	241.2

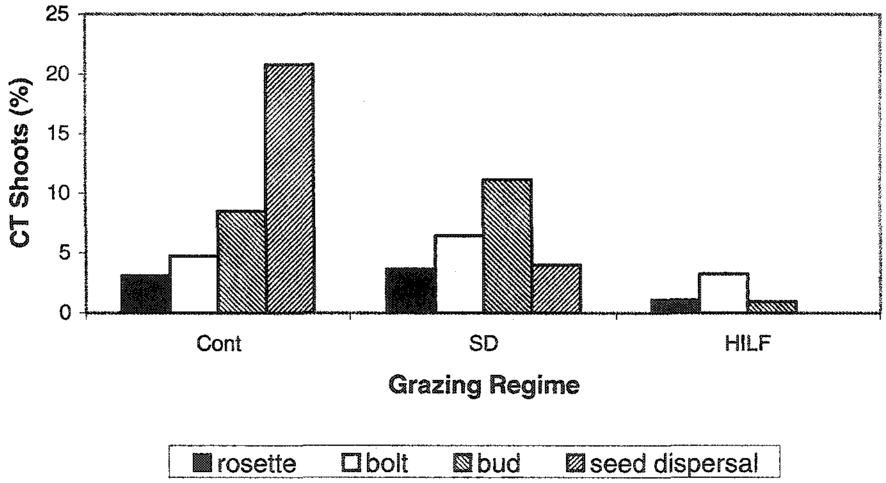
[1] Within a column and site, means with different letters indicate significant differences, $P \leq 0.05$.

Figure 4.1. Proportion of CT shoots at varying phenological stages across four sites and four grazing regimes in 2001 (A) and 2002 (B).

(A)



(B)



5. SYNTHESIS: INCORPORATING GRAZING STRATEGIES INTO WEED CONTROL

Canada thistle (CT) is a pervasive weed in western Canada, and has an extensive root system and aggressive growth strategy that allows it to spread and thrive in many environments. Consequently, CT is present within nearly all types of plant communities, including annual cropland, native rangeland, tame (i.e. introduced) pasture, urban landscapes, roadsides and railways, as well as waste areas (Frankton and Mulligan 1987; Moore 1975). The purpose of this research was to evaluate Canada thistle abundance and forage production responses to varied defoliation intensity and frequency of surrounding sward vegetation, and investigate the ability of rotational grazing systems with cattle to achieve direct control of CT. These results are an initial attempt at discovering the underlying mechanisms that allow CT spread in permanent pasture, as well as address the possibility for land managers to use cattle as a practical biocontrol agent.

5.1 Forage – Weed Interspecific Competition

In the first study (Chapter 3), a clipping experiment conducted over 3 years showed that repeated, intensive defoliation simulating continuous grazing caused the greatest levels of CT density and biomass, as well as the lowest forage production. Conversely, deferred defoliation until peak biomass was the most effective at increasing forage production and reducing CT. Of the rotational systems, the high intensive, low frequency (HILF) regime tended to increase forage production and reduce CT more readily than the short duration (SD) system, indicating forage levels were more closely dependent on the frequency of defoliation (or length of the recovery period) rather than the intensity of defoliation. This result was attributed to a high tolerance of introduced forage grasses to defoliation, and their ability to maintain rapid growth even at relatively high levels of defoliation (e.g. 70-80%).

Moreover, CT abundance was influenced by the growth of adjacent forage, which in turn, reflected strong interspecific competition between the weed and adjacent grasses, possibly due to below ground competition for water and nutrients. Although fertilization tended to augment the differences among treatments and caused treatment differences to be evident in a shorter period, trends among treatments were consistent regardless of fertility. Treatment responses also varied among sites, likely due to inherent differences in vegetation composition, and local growing conditions including soil type, nutrient levels, available moisture, and other disturbances.

Overall, these results indicate that an important tool in weed control, at least for CT, includes strategies to maintain a high vigor of the forage stand. Management strategies that increase or enhance the growth of grasses places greater competitive pressure on the weed, and results in a reduction in CT. Although the likelihood of CT entry into pastures was not investigated in this study, it is also likely that the maintenance of a vigorous grass sward with little or no microsites for CT establishment (e.g. bare soil) will also limit weed populations in perennial pasture.

Additional research is required addressing the specific conditions under which interspecific competition is important in regulating weed abundance. This includes testing of the relationship between different combinations of pasture weed and forage grass species, under a wider range of conditions such as moisture and fertility.

5.2 Grazing as a Tool for Biocontrol

The second study (Chapter 4) investigated the possibility of using cattle grazing systems as a direct means of controlling CT. This was conducted on a total of 4 sites over a period of 3 years. This study was complementary to the previous investigation in that it assessed the combined indirect effects (i.e. competitive shifts) and direct effects (i.e. defoliation and/or trampling impact of cattle) on a target weed. Results of that study showed that a continuous grazing regime maintained and/or increased severe CT infestations in perennial pastures as animals were able to selectively graze plants. Similar to that seen in the previous clipping study (Chapter 3), cattle grazing in a HILF rotational system reduced CT densities, and resulted in greater reductions than a more conservative SD grazing system. Additionally, the HILF system had the greatest impact in altering CT vigor (i.e. height) and development (i.e. prevented flowering). Two intense defoliations annually over a 2-3 yr period were able to nearly eliminate CT. There would still likely be CT seeds in the soil seedbank, and if patches of bare soil were to open, the chance of CT sprouting from seed exists. However, since there are many annual seeds present in the seedbank (more prolific seed producers than CT), it is questionable that CT would be the plants to establish in these microsites.

In most cases there was no difference in CT height between the continuous and SD treatments, as cattle avoided defoliating these plants in both of these treatments. Similarly, the stage of plants observed in the SD treatment resembled those found in the continuous more than in the HILF treatment.

In this study, it was impossible to clearly distinguish between the impact of altered interspecific competition between CT and forages, and the direct affect of cattle to

CT plants. However, given the earlier finding that interspecific competition from grasses was able to significantly reduce, though not eliminate CT, any incremental decline in CT in this study may be attributed to the forced utilization of CT documented in the HILF grazing system. In contrast, very little actual use (i.e. defoliation) of CT occurred in either the continuous or SD systems, likely due to the limited grazing pressure (i.e. ratio of forage demand to forage supply) achieved during grazing.

Notably, the HILF system resulted in the greatest reduction in CT among grazing treatments despite having the greatest year-long stocking rate. This result further reinforces the notion that grasses in perennial pastures of central Alberta are well-adapted to the intense defoliation required to remove CT above-ground biomass, provided the recovery period is long enough to allow for recovery of the grasses. Conversely, CT does not appear to be tolerant of defoliation. The extent to which the decline in CT was due to direct defoliation during cattle foraging, or simply trampling under high stock densities, or even incremental disturbances such as increased disease pressure, remains unknown and warrants further research.

This study also measured CT density and grass production after the grazing treatments ended and pastures returned to a continuous grazing system. Across all sites, the HILF system continued to demonstrate little to no CT growth after formal treatments ceased, and tended to have greater grass production over both the continuous, and often the SD system. This result indicates that the reduction in CT stems were more than superficial, with a reduction in below ground root density and biomass also probable. However, more definitive testing of this characteristic (i.e. root dynamics) of weed growth would also be worth investigating in future studies.

In contrast to the HILF system, SD grazing and particularly continuous grazing, allowed CT stems to consistently reach advanced stages of growth, with the majority of stems able to flower and produce seed, thereby presenting a risk of weed spread. Weed spread is an obvious problem across western Canada where producers with poor management and high weed populations may serve as areas for new infestations of surrounding regions, particularly during opportune times (e.g. widespread drought such as in 2002). Advanced staging of CT plants also generally resulted in lower quality of CT as potential forage, with lower N and greater ADF levels. These characteristics likely further reinforced the avoidance of CT by cattle in the continuous and SD treatments, and the more frequent selection of other herbs (i.e. grasses) by cattle, thereby reducing their vigor. In the HILF treatment, the vast majority of CT stems were maintained in the rosette stage, resulting in short CT plants, with little development to flowering. Maintaining CT in a young stage of growth had the added benefit of maintaining these shoots in a more palatable and nutritious condition. Rosette plants were typically greater in N and water content and lower in ADF, indicating they had greater nutritive value to cattle and might be more palatable, relative to advanced CT plants.

5.3 Conclusion

Difficult to control perennial pasture weeds such as CT are likely to continue to exist in pastures of central Alberta and similar regions. However, the overall results of this research provided very positive results indicating that defoliation regimes affect both CT and forage abundance. Moreover, proper grazing management, particularly through the use of specific grazing systems, was shown to be a potential tool to help in the control of CT, either by manipulating forage-weed competitive relationships, or by forcing direct defoliation/damage to the weed. In this study, cattle grazing in an HILF system was shown to be an effective tool and management strategy to help control CT. In essence, this study has provided pasture managers with another option when evaluating methods on how to control CT. The use of grazing as a biocontrol tool may be particularly important in areas where the use of other control options, including the use of herbicides, is not possible, either due to environmental restrictions (i.e. around wetlands) or logistical problems (e.g. in rough terrain where sprayers can't access). Combining grazing with other management practices such as the use of herbicides and appropriate fertilization practices will enhance overall opportunities for successful weed control in pastures of western Canada's Parkland region.

The SD grazing regime representing the "take half, leave half" principal of grazing indicated that in the Parkland region, this system does not maximize grass production or sward competitiveness with CT. A utilization of 50% is a commonly applied safe use factor (SUF) on many rangelands and permanent pastures, based on the principle that by leaving half of plant biomass behind, forage regrowth and vigor will be maximized. This study shows that the SD system does not accomplish this in pastures containing the highly grazing tolerant species found in this area, and rather a high intensity of 70-80% (accompanied by at least 8 weeks rest), maximizes pasture production over SD grazing. More research will be required to evaluate traditional notions of SUF's for the Parkland region.

Finally, it should be noted that the use of intensive grazing systems may not be appropriate in all situations. For example, in regions with less rainfall where litter retention is important to maintain optimal pasture hydrologic function, the removal of high amounts of standing biomass, thereby potentially reducing litter, may increase the risk of soil xerification and even erosion. Additionally, the use of 'forced' grazing of weeds may not be appropriate for cattle that are being grazed for rapid and high weight gain (i.e. grassfed yearlings), as these animals would be forced to consume lower quality material (both grass stems and CT plants) and potentially sacrifice intake rates in their reluctance to feed on unpalatable weeds such as CT. In contrast, cows are more likely to graze CT with little adverse effects to their preformance. Additionally, the incremental costs associated with fencing large paddocks into smaller areas and servicing them (i.e. providing water), as well as the labour required to monitor and move cattle, may also reduce the attractiveness of using grazing systems requiring small paddocks. However, the widespread availability of low-cost electric fencing, and the espoused benefits of rotational grazing, even with a simple system of several pastures per herd, are likely to increase pasture production and may help reduce the population of weeds such as CT in pastures. Further research is also recommended to identify the optimal type of rotational grazing system, including size and composition of pasture, specific grazing levels and appropriate rest periods, etc. that will optimize both pasture sustainability (including weed control), and animal production under western Canadian conditions.

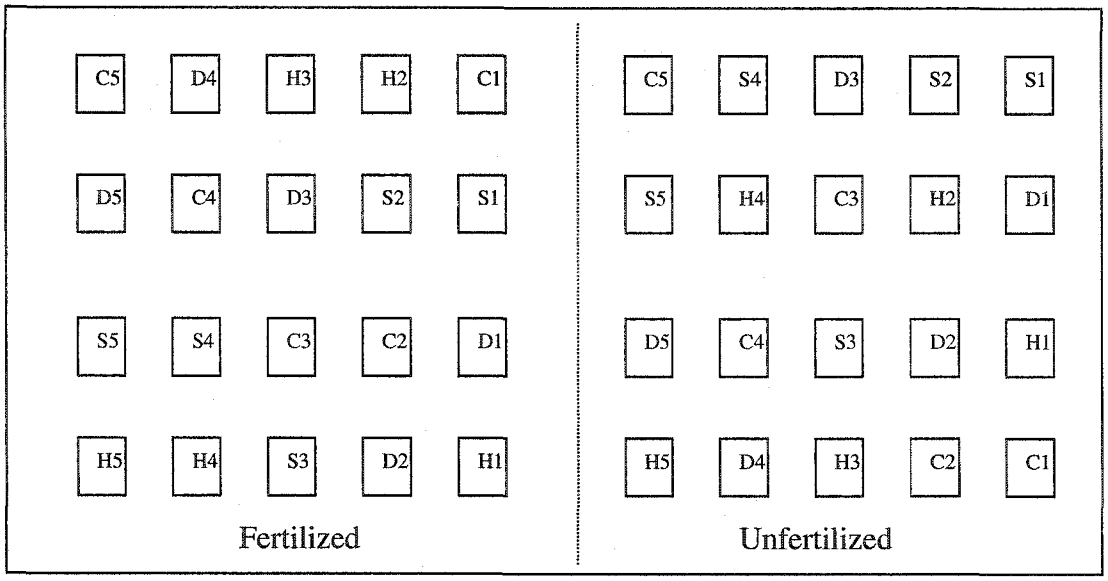
5.5 Literature Cited

Frankton, C. and G.A. Mulligan. 1987. Weeds of Canada. Publication 948. NC Press Ltd., Toronto, Ontario. 217 pp.

Moore, R.J. 1975. The biology of Canadian weeds 13: *Cirsium arvense* (L.) Scop. Can. J. Plant Sci. 55:1033-1048.

APPENDIX 1: Site Maps for the Clipping Study and Grazing Study

Appendix 1.1 Sample site map for the clipping study (Barrhead site).



Note: Different letters represent the different treatments and the different numbers represent the repetitions of the treatments.

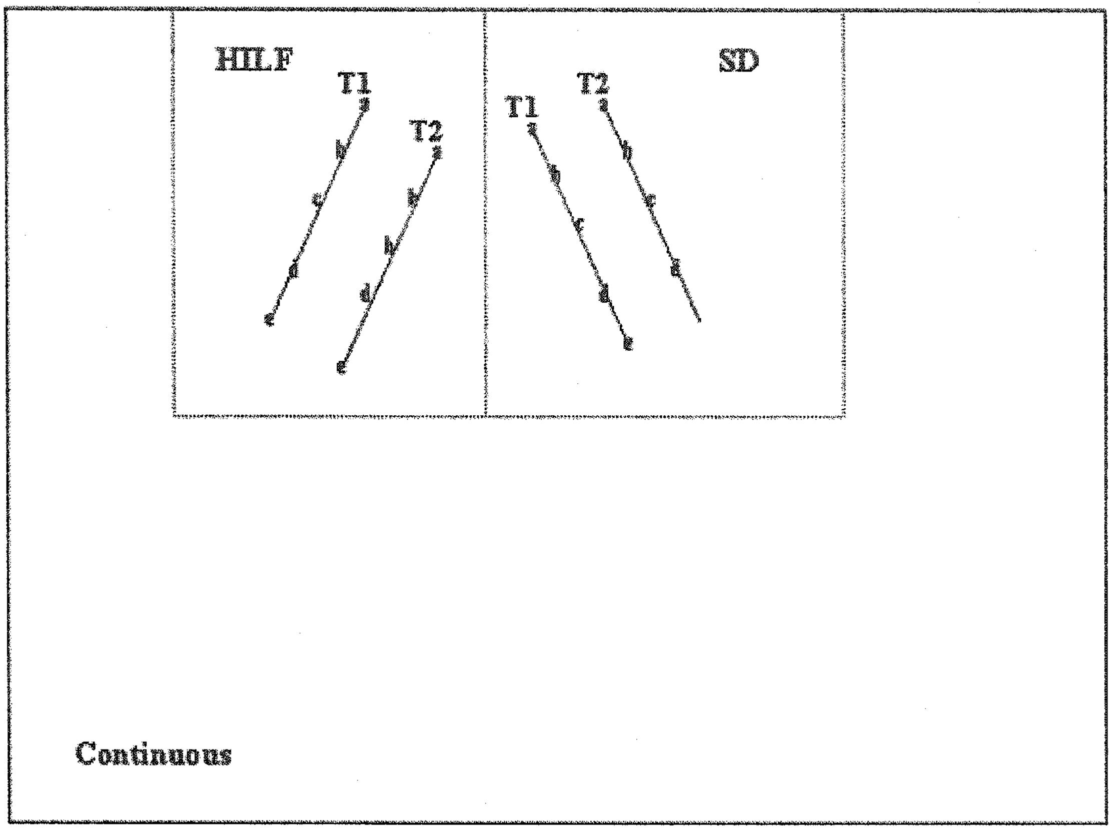
D = Deferred Treatment

H = HILF Treatment

S = SD Treatment

C = Continuous Treatment

Appendix 1.2 Sample site map for the grazing study.



______ = Permanent Fencing

_ _ _ _ = Electric Fencing

T1 = Transect Line One

T2 = Transect Line Two

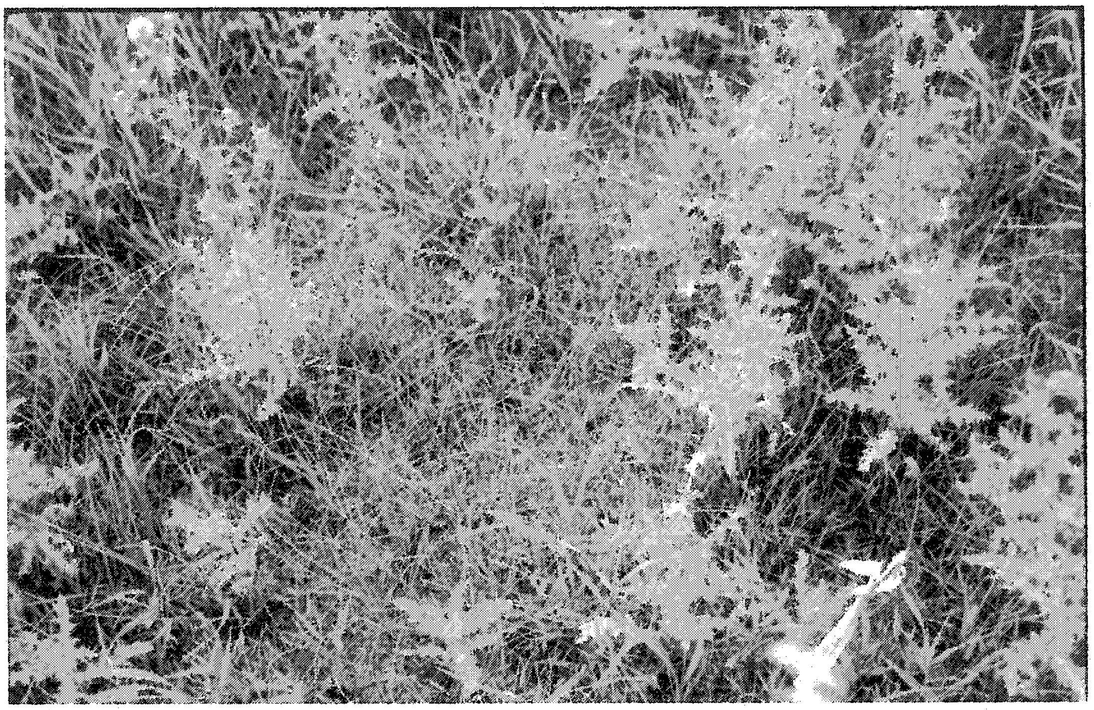
Letters a-e = Permanent 0.5 m^2 quadrat placement on the transects

APPENDIX 2: Clipping Trial Photos

Appendix 2.1 Pictures showing the effects of each of the four forage defoliation treatments (A) Continuous, (B) SD, (C) HILF, and (D) Deferred, on the condition of forage and CT stand after two years of treatment.

(A)

(B)



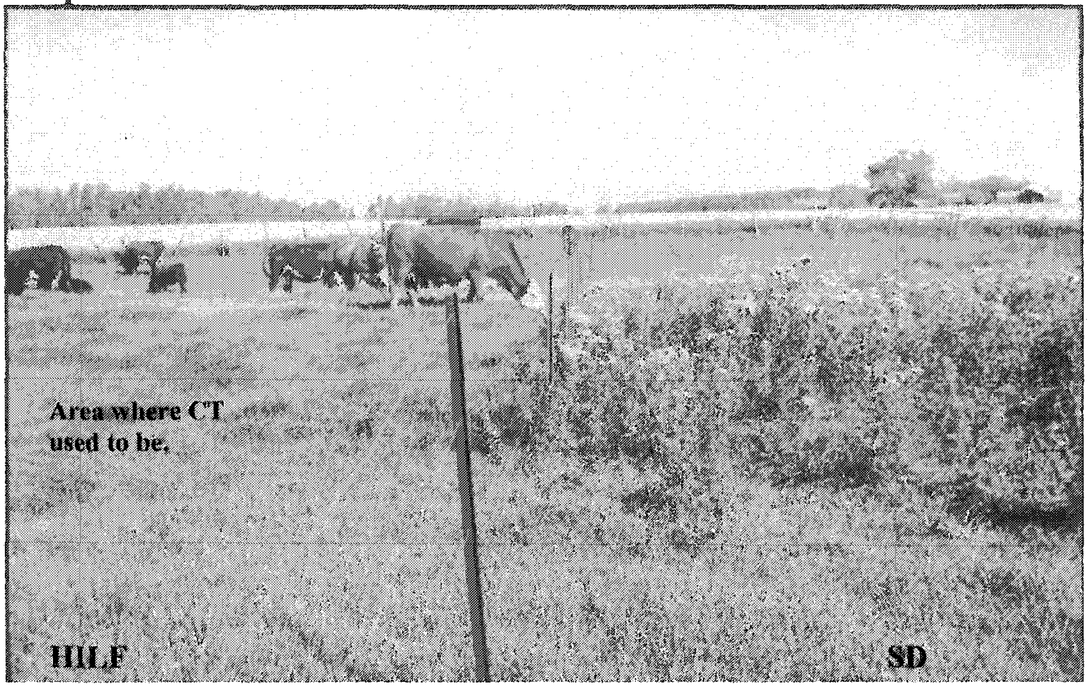
(C)

(D)

APPENDIX 3: Grazing Trial Photos

Appendix 3.1 Grass utilization in the HILF (right) treatment compared to the SD (left) treatment immediately after grazing the HILF sub-pasture (SD was grazed 4 days prior).

Appendix 3.2: Difference in CT populations after the HILF (left) and SD (right) treatments have been implemented. Note that the CT initially extended uniformly across both treatments, with CT now removed by cattle in the HILF sub-pasture.



Appendix 3.3 Difference in CT populations between the HILF (right) and continuous (left) treatments. Note that CT initially extended uniformly across both treatments, and CT has now been removed by cattle in the HILF treatment.

Appendix 3.4 Forage regrowth within the SD (right) and HILF (left) treatments after the HILF treatment has been rested for 8 weeks and the SD has been rested for 4 weeks.