The Impact of Tillage Intensity on the Recruitment of False Cleavers (*Galium spurium* L.)

BY
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ABSTRACT

Danielle, Reid J. M. Sc. University of Manitoba, April 2003. The Impact of Tillage Intensity on the Recruitment of False Cleavers (*Galium spurium* L.) Major Professor: Dr. Rene Van Acker

By altering the microsite conditions, including soil temperature and soil moisture, tillage intensity can influence the germination and emergence of seeds. False cleavers (*Galium spurium* L.) recruitment may be reduced when weed seeds remain on or near the soil surface. Tillage affects the placement of weed seeds in the soil. False cleavers infestations may be limited by the intensity of tillage used in a given management system. In the summer of 2001 and 2002, field experiments were conducted to investigate the impact of tillage intensity on the recruitment of false cleavers. Experiments were conducted at two locations, and considered three tillage treatments; no additional tillage, spring and fall tillage and fall tillage only. Spring emergence counts indicated that recruitment was significantly greater in tilled treatments relative to untilled treatments in three of four site years. Spring gravimetric soil moisture measured from 0-5cm did not vary significantly between the tillage treatments at either location, in either year. Spring soil temperature measured at 4cm was significantly different between tillage treatments in three of four site years. However, actual temperature differences recorded between treatments were not regarded as being biologically significant. In the spring of 2002, additional measurements were included to investigate the variation in soil temperature and moisture at various soil depths. Temperature amplitude was greater at the 1cm verses the 4cm depth. This consisted of both greater maximum temperatures and lower minimum temperatures at 1cm verses 4cm. Volumetric soil moisture levels also varied with depth (0-2, 2-4, 4-6cm), showing a tendency for the soil surface layer to be

driest. Thus, temperature and moisture differences between tillage treatments did not appear to be controlling the spring false cleavers recruitment. Rather, differences in soil temperature and moisture experienced by false cleavers as a result of distinct seed placement in tilled verses untilled treatments was influencing spring false cleavers recruitment. In the untilled treatments seeds were concentrated on or near the soil surface. As such, they were exposed to extreme temperature and moisture conditions and to solar radiation. False cleavers germination is inhibited by the prolonged exposure to light. False cleavers seedling recruitment in the fall was very low for all tillage treatments. Extremely low moisture conditions may have led to the reduced fall recruitment. The low fall recruitment was also a reflection of the summer annual growth habit of the seed population used in our experiment. No fall emergence counts were done in 2002.

GENERAL INTRODUCTION

In North America "cleavers" is the common name used to describe two species; *Galium aparine* L. (True cleavers) and *Galium spurium* L. (False cleavers). Both of these species are members of the Rubiaceae or Madder family, and are currently listed as a class 2 primary noxious weed according to the Canada Seed Act: Weed Seed Order (SOR/86-836) (Anonymous 1986). It is believed that in North America, the predominant species in agricultural fields is *Galium spurium*. Based on a relative abundance index, cleavers was ranked as one of the top 20 weed species in the 2002 Manitoba Weed Survey (Leeson et al. 2002). Cleavers is considered a competitive weed, leading to yield losses and reduced crop quality (Malik and Vanden Born 1987a).

Initially, in Western Canada the establishment of cleavers appeared to coincide with an increase in the acreage of land seeded to canola (*Brassica napus* L.). This was largely due to the absence of effective chemical control for cleavers in canola and crop seed contamination. However, since the advent of herbicide resistant canola varieties, control of many weed species, including cleavers, has been enhanced in this crop. As a result, it was believed that cleavers would no longer be a significant pest on the Canadian prairies. However, the relative abundance of cleavers in Manitoba has not changed from 1997 to 2002, suggesting that the introduction of herbicide tolerant crop varieties is not significantly reducing the occurrence of cleavers (Leeson et al. 2002).

In addition to the natural hardiness of this weed, control is further complicated by the development of herbicide resistance. In Canada, a biotype of cleavers exhibiting multiple resistance to Group 2 (ALS Inhibitors) and Group 4 (Synthetic Auxins) herbicides was discovered in Alberta in 1996 (Hall et al. 1998). The presence of

herbicide resistant biotypes within Canada reinforces the importance of identifying non-chemical methods for the control of cleavers.

Cleavers recruitment is sensitive to soil moisture level and seeding depth (Boyd and Van Acker, 2003). Responses are partially related to the inhibitory effect of light exposure on cleavers seed germination. Even at very low light intensities recruitment is reduced when cleavers seeds are exposed to light after 36hours of imbibition (Malik and Vanden Born 1987c). In the field, tillage moves weed seeds within the soil profile. The ultimate placement of the seeds is dependant on the intensity of the tillage operation used. Where no tillage is applied, weed seeds are concentrated on, or near, the soil surface. Where soils are tilled, the weed seeds tend to concentrate near the lower region of the tillage zone. Differences in placement will affect the conditions that weed seeds are exposed to. Tillage may also directly affect the conditions of the soil environment by altering the soil physical properties and surface residue cover. These changes in soil conditions, specifically soil temperature and soil moisture, may also affect weed seedling recruitment. Thus, tillage may impact the conditions experienced by weed seeds either directly by affecting soil properties or indirectly by changing the position of seeds within the soil profile. Varying the intensity of tillage may impact the establishment and success of cleavers on agricultural fields.

CHAPTER 2

Literature Review

2.1 Introduction

In North America "cleavers" is the common name used to describe two species; *Galium aparine* L. and *Galium spurium* L. Both of these species are members of the Rubiaceae or Madder family, and are currently listed as a class 2 primary noxious weed according to the Canada Seed Act: Weed Seed Order (SOR/86-836) (Anonymous 1986). *G. aparine*, "true cleavers" and *G. spurium* "false cleavers" are almost identical in appearance and growth habit, making them virtually indistinguishable by visual inspection alone. The only reliable diagnostic characteristic that can be used to separate the two species is the chromosome number. Unfortunately, cytological investigations are laborious and often impractical. As a result, most researchers and producers do not make the distinction between the two species, and they refer to the weed generally as cleavers. Both *G. aparine* and *G. spurium* are believed to be present as weeds in Canadian grain fields (Malik and Vanden Born 1988). However, much of the research originating in Canada identifies the predominant species as *G. spurium*. This differs from Europe where *G. aparine* is identified as the more troublesome species on agricultural lands.

For a long period *G. aparine* has been a significant weed in European farmlands. More recently, cleavers have become an important pest in Canadian agricultural lands. Initially, the establishment of cleavers seemed to coincide with an increase in the acreage of land seeded to canola. This was largely due to the absence of effective chemical control options for cleavers in this crop. This led to yield reductions resulting from competition effects and harvesting difficulties, as well as, reduced oil quality associated

with weed seed contamination. However, since the advent of herbicide resistant canola varieties, control of many weed species including cleavers was enhanced in this crop. As a result, it was believed that cleavers would no longer be a significant weed species on the Canadian prairies. However, with its ability to withstand many chemical controls, and its prolific seed production, cleavers have not disappeared as an agricultural pest, and in fact, the extent of cleavers on the prairies continues to expand.

The control of cleavers on the prairies has focused primarily on chemical methods. Rotations, especially those including herbicide tolerant canola varieties, seem to minimize the rate of cleavers population growth. However, with the development of herbicide resistance in cleavers, there is interest in other cultural methods for control or reduction of cleavers. At present, the extent of cleavers in Manitoba is somewhat limited, focused largely in the North West region of the province. However, it is unlikely that cleavers growth will be restricted to its current location. Thus, if more effective controls are not determined, cleavers will likely continue to spread beyond its current bounds. Fortunately, this species exhibits certain environmental sensitivities that suggest that the tillage regime may impact the establishment and success of this weed. Some tillage regimes may limit the spread and intensification of this species in agricultural fields in Manitoba.

2.2 Species Description

2.2.1 *G. aparine*

In North America, *G. aparine* is considered both a native and an introduced species (Malik and Vanden Born 1988). Native populations were believed to be present

in various habitats including deciduous woods, thickets and rocky coastal bluffs (Moore 1975). Introduced populations of *G. aparine* were brought to North America from Europe, likely through the transport of seed grain. The following plant description is based on observations made by various scientists and reported by Malik and Vanden Born (1988).

G. aparine is characterized by having numerous branched green stems with recurved thorn-like spines. In cross section, the stems are quadrangular with predominant ribs, from which the spines extend. Growth is considered semiprostrate or climbing ascending, with stems adhering to or lying on adjacent vegetation. Each stem can grow up to 120 cm long. The leaves are usually green with hairs on the upper surface and forward directed spines on the midrib of the underside. Leaves are simple, narrow and single-veined. They range in size from 30 to 60mm long and 3 to 8 mm broad, and occur in whorls of four to eight. White flowers are arranged in cymes on a peduncle, which extends from the axils of the leaf whorls. Two to five flowers may be present on each peduncle. The flowers are approximately 2 mm in diameter and exhibit a bisexual nature. Each flower produces a shizocarp with two carpels, forming two globose mericarps. The fruits are oval, 2 to 4 mm long and range in color from gray to dark brown. The surface of the fruit is normally covered with hooked bristles extending from tuberculate bases. These bristles enable the fruit to adhere to a variety of surfaces. Sometimes the fruits are only sparsely spiny or smooth, though this condition is much less common. Each plant is estimated to produce an average of 300-400 seeds annually. However, some plants have been known to produce as many as 3500 seeds under controlled greenhouse conditions

Cytological studies of G. aparine have been extensive. The examination of broadly distant populations has resulted in the identification of various levels of ploidy, as expressed by chromosome numbers ranging from 2N = 22 to 2N = 88 (Moore 1975). In North American populations, the average number of chromosomes present in the cells is 2N = 64 or 66 (Malik and Vanden Born 1988).

Two forms of *G. aparine* are distinguished by the presence or absence of spines on the fruits. *G. aparine* forma aparine produces fruits with spines; whereas, the fruits of *G. aparine* forma intermedium do not possess spines (Malik and Vanden Born 1988).

2.2.2 *G. spurium*

Unlike *G. aparine*, no native populations of *G. spurium* exist in North America. This species is solely an introduction from Eurasia (Malik and Vanden Born 1988; Moore 1975). The following description is based on personal observations made by Malik and Vanden Born (1988).

Stems of this species are longer (up to 200cm), stiffer, rougher and more branched than *G. aparine*. Leaves of *G. spurium* are a lighter green color and are more "sticky" than those of *G. aparine*. They range in length from 12 to 62 mm and in width from 2.5 to 6 mm. Flowers of *G. spurium* are pale yellow or yellowish-green in color, rather than white. The fruits produced are often slightly smaller than those of *G. aparine*, with a mean size of 1.5 x 2.5mm.

Chromosome number represents the only reliable distinguishing feature between the two species. Chromosome counts performed on a variety of populations indicate that

no polyploidy occurs in *G. spurium*, resulting in a diploid number of 2N=20 only (Malik and Vanden Born 1988).

Like *G. aparine*, *G. spurium* is divided into two different forms based on fruit characteristics. *G. spurium* forma vaillanttii has spiny fruits. *G. spurium* forma spurium has smooth fruits (Malik and Vanden Born 1988).

2.3 Geographical Distribution

G. aparine is found in temperate zones worldwide, including all of Europe, and parts of Siberia and central Asia (Moore 1975). *G. aparine* has also been identified in select tropical regions. However, these are generally at high altitude locations (Malik and Vanden Born 1988).

In Canada, it is suggested that *G. aparine* is present in all provinces apart from Prince Edward Island (Moore 1975). Surveys have indicated that *G. aparine* is present in southern parts of British Columbia including Vancouver Island, south-central Alberta, Saskatchewan, and Manitoba, southeastern Ontario, south-central Quebec as well as all of the eastern provinces except for PEI (Moore 1975).

G. aparine favors environments that are moist and shady (Malik and Vanden Born 1988). This species is often found growing in deciduous woods, thickets and coastal bluffs, which are considered the native habitat for *G. aparine* (Moore 1975). However, it is also present in non-native environments including, grain fields, waste grounds, fence-rows, barnyards and pastures (Malik and Vanden Born 1988).

It is believed that *G. spurium* was introduced into Canada as a contaminant in seed imported from Eurasia by early settlers (Moore 1975). Herbarium samples of this

species date back to 1878, with the first recorded specimen from Belleville, Ontario (Moore, 1975). In Canada *G. spurium* has been identified at the southern tip of Vancouver Island, across the Prairie Provinces and in southwest Ontario and Quebec (Malik and Vanden Born 1988). The distribution of this species appears to be less extensive than that of *G. aparine*. However, it is unclear if *G. aparine* is truly more prevalent, or if the greater presence of *G. aparine* in Canada is related to the misidentification of species.

G. spurium is intolerant to shade, and favors relatively dry and sunny habitats (Malik and Vanden Born 1988; Moore 1975). This species is often found in cultivated fields, coastal areas, roadsides, field borders, dry open woods, gardens and waste grounds (Malik and Vanden Born 1988). It has been identified in association with a variety of crops, including canola (*Brassica napus* L.), wheat (*Titicum aestivum* L.), barley (*Hordeum vulgare* L.), oat (*Avena sativa* L.), flax (*Linum usitatissimum* L.), field pea (*Pisum sativum* L.) as well as forage seed crops (Malik and Vanden Born 1988).

As is the case for most North American weed surveys, in Manitoba no distinction has been made between the two *Galium* species, *G. aparine* and *G. spurium*. As a result, most weed surveys use the general term, "cleavers" when documenting the presence of either species. According to the most recent Manitoba weed survey, the greatest relative abundance of cleavers occurs in four ecoregions; the Aspen Parkland in the Grandview and Stockton ecodistricts, the Mid-Boreal Upland in the Duck Mountain and Riding Mountain ecodistrict, the Boreal Transition ecoregion in the Swan River ecodistrict and the Lake Manitoba Plain in the Emerson, Lundar and Portage ecodistricts (Leeson et al. 2002). Intermediate infestations were found in the Interlake Plain in the Gimli and

Ashern ecodistricts, Lake Manitoba plain in the Dauphin ecodistrict and in the Aspen Parkland ecoregion in the St. Lazare ecodistrict. In the 2002 survey, cleavers have also been observed in locations where they were not present in previous surveys, including the Lake Manitoba plain in the McCreary ecodistrict, Aspen Parkland in the Hilton ecodistrict, and the Southwest Manitoba Uplands in the Pembina Hills and Killarney ecodistricts. Lesser infestations have also been identified in the Manitou ecodistrict in the Aspen Parkland ecoregion. According to the 2002 Manitoba provincial survey, cleavers are considered absent from the remainder of the surveyed area (Leeson et al. 2002). Based on the comparison of relative abundance data from surveys done in the 1970's to that completed in 2002, the rank of cleavers has gone up 19 positions, suggesting an increase in either frequency, field density or field uniformity of cleavers over that period (Leeson et al. 2002).

2.4 Agricultural Impacts

Cleavers have been identified as a significant pest in various crops throughout the Prairie Provinces of Canada. When present within a field, this weed often leads to reduced yields and a loss of quality. According to the Canada Seed Act, cleavers are listed as a class 2, primary noxious weed (Anonymous 1986). This implies a zero tolerance limit for cleavers in all grades of pedigree seed including, foundation, registered and certified seed (Anonymous 1986). This ultimately impacts producers of cereal, forage and oilseed crops. However, cleavers are a particularly serious problem for canola seed producers, as the size and shape of the seeds are similar. This makes the mechanical separation of cleavers seed from canola seed difficult.

Cleavers is also a relatively competitive weed. In Europe, cleavers (*G. aparine*) has been identified as the most competitive common broad-leaved weed in winter cereals (Wilson and Wright 1987). A study conducted in Oxford, England showed that each cleavers plant·m^{-2} reduced wheat grain yield by 0.7 to 2.9% (Wilson and Wright 1987). In Canada, researchers discovered that high infestations (100 plants·m^{-2}) of *G. spurium* reduced rapeseed yields by between 4 and 28%, depending on the emergence date of the weed relative to the crop (Malik and Vanden Born 1987a). In addition to the effects of direct competition, the presence of cleavers can affect crop quality. Even at relatively low infestation levels, canola oil quality can be dramatically reduced by the presence of cleaver seed (Malik and Vanden Born 1987a).

Cleavers is described as a highly prolific seed producer. On average a single *G. spurium* plant produces between 300 and 400 seeds, with a maximum production of 3500 seeds when grown under ideal conditions (Malik and Vanden Born 1988). At high infestation levels, *G. spurium* emerging with a rapeseed crop, or one week after the crop, resulted in a seed contamination level of 31 and 72 seeds·g^{-1} of rapeseed, respectively (Malik and Vanden Born 1987a).

As with most weed species, the threat of herbicide resistance is a concern for producers who depend mainly on chemical weed control. In the case of cleavers, herbicide resistance has been expressed in biotypes of both *G. aparine* and *G. spurium*. In Europe, a number of different populations of *G. aparine* have been found to exhibit varying responses to the herbicide, fluroxypur (Hill et al. 1996). In Canada, biotypes of *G. spurium* have been identified that are resistant to a number of Group B/2 (ALS inhibitors) and Group O/4 (Synthetic auxin) herbicides. In Canada, resistance in cleavers

was first reported in Alberta in 1996 (Hall, et al. 1998). False cleaver plants present in a field sprayed with triasulfuron/bromoxynil appeared to be virtually unaffected by the herbicide. Further studies conducted on this biotype, identified it as being cross-resistant to thifensulfuron/tribenuron (Hall, et al. 1998). As well, acetolactate synthase-resistant false cleavers were found to exhibit a cross-resistance to quinclorac, a Group O/4 (hormone mimic) herbicide (Hall et al. 1998).

2.5 Growth and Development

Both *G. aparine* and *G. spurium* are described as having an annual growth habit. The first flush of germination occurs in the spring, usually around late April or early May, depending on the location and environmental conditions (Malik and Vanden Born 1987b). In a study conducted in Edmonton, Alberta, seeds of *G. spurium* were sown in mid-May, and they emerged approximately 2 weeks after being seeded (Malik and Vanden Born 1987b). Flowering began in early July when the plants had reached the 8 to 10 node stage, and continued into late August (Malik and Vanden Born 1987b). Seed formation began in early July, with seeds first developing at the lower parts of the plant. By the end of August, seeds occurring within the lower ¾ of the plant were brown and fully mature. It is also at this point when "rejuvenation" was observed in some plants included in the experiment. "Rejuvenation" refers to the formation of new growth after senescence has already begun and the plant foliage has turned brown (Malik and Vanden Born 1987b). This new growth often occurs at the tops of the main shoots, at the terminal points of some of the branches, and at some nodes (Malik and Vanden Born 1987b). In a greenhouse study, Moore (1975) observed "regeneration" in *G. aparine*

plants. Moore (1975) described the regrowth as dwarfed green shoots that continued to grow from the dried flowering stems. Unlike Malik and Vanden Born (1987b), Moore (1975) did not observe the same regrowth in *G. spurium*.

In Ontario, naturally occurring *G. aparine* was observed to flower from late May until mid-June (Moore 1975). Seed maturation began in late June and ended in mid-July (Moore 1975). However, this growth pattern is not universal. Rather, it tends to vary according to the location from which the plant populations are sourced. Differences in growth patterns have been observed for populations of *G. aparine* when obtained from widely separated locations (Moore 1975). This was shown in an experiment by Moore (1975), where seeds from Illinois, California, Ontario and Oklahoma were collected and grown under standard greenhouse conditions. After only six weeks, the populations showed apparent differences in their growth rate (Moore 1975). This form of altered response is related to genetic differences associated with varied selection pressures occurring in the different habitats or regions. Populations of the same species that exhibit genetic differences are referred to as ecotypes (Baskin and Baskin 1998a). In Japan, two ecotypes of *G. spurium* have been identified (Masuda and Washitani 1992). These two ecotypes exhibit contrasting thermal dormancy characteristics, resulting in one spring emerging and one autumn emerging form. Studies investigating the differences between hedgerow and arable *G. aparine* populations have indicated that they differ developmentally and in their requirement for vernilization (Bain and Attridge 1988;Van der Weide 1992).

Differences in the growth response of seeds to environmental conditions can also be the result of preconditioning effects. Preconditioning refers to the impact of the

environmental conditions experienced by a parental plant during maturation, on the growth of its progeny (Baskin and Baskin 1998a). The conditions during plant maturation can impact both the chemical compounds found within the seed, as well as, the physical form of the seed. In terms of the chemical constituents of the seed, the location of a seed on the parent plant is important, as the proportion of a given chemical transferred from parent to progeny is related to the amount present in the parent plant tissue. The environmental conditions, such as temperature and light, may also influence the chemical composition of a seed and as a result, impact germination. In terms of physical impacts, the environmental conditions at maturation can lead to differences in seed size, shape and color. The resulting impact of these morphological differences may or may not be significant. There is some evidence to suggest that seed vigor may vary with morphology which would likely influence survivorship (Baskin and Baskin, 1998a).

Under certain environmental conditions a biennial habit has been observed in both *G. aparine* and *G. spurium* (Malik and Vanden Born 1988). In West Germany, *G. aparine* is reported to be one of the most winter hardy weeds of fall sown rape, wheat, barley and rye (Malik and Vanden Born 1988). In North America, *G. spurium* plants have successfully over-wintered in agricultural fields (Malik and Vanden Born 1987a). In a field experiment located in Edmonton, Alberta, Malik and Vanden Born (1987a) observed that some fall-germinated seeds were able to survive over the winter of 1983-1984. From this experiment, Malik and Vanden Born (1987b) have suggested that survival depends on the developmental stage of the plant at first frost, as well as, the severity of the winter conditions. If at the time of the first frost the plant is within a vegetative growth stage, including the seedling stage, then winter survival was generally

high (Malik and Vanden Born 1987b). However, if frost occurred after the plants had reached flowering they did not survive (Malik and Vanden Born 1987b). Survival was also hindered by extremely harsh winter conditions. In Edmonton, Alberta, during the winter of 1982-1983, the combination of very low temperatures and minimal snow cover limited the survival of fall-germinated seeds (Malik and Vanden Born 1987b).

Seeds that germinate in the fall and successfully over-winter resume their growth in the following spring. These seedlings appear different from those that were spring germinated (Malik and Vanden Born 1988). Growth is prostrate, with more numerous branches, shorter internodes and shorter leaves. Malik and Vanden Born (1988) did not comment on the potential effect that these differences might have on seed production or plant competitiveness.

2.6 Dormancy

Dormancy is described as an internal condition of a seed where by germination is inhibited under otherwise adequate environmental conditions (Benech-Arnold et al. 2000). Seed dormancy can be influenced by a number of different factors including conditions internal and external to the seed. For a given species, the act of identifying the factors that influence dormancy and interpreting their interactions is difficult. As a result, dormancy behavior in plant species is an area of science that is not well developed. This is true for both *G. spurium* and *G. aparine.*

Based on the timing of occurrence, dormancy can be broken into two forms, primary dormancy and secondary dormancy. Primary dormancy is considered an innate state of dormancy that occurs only in newly formed seeds. The results of studies

investigating primary dormancy in *G. aparine* have been contradictory. Some have indicated that *G. aparine* requires a chilling period for successful germination, while others suggest that freshly harvested seed has a high capacity for germination (Sjostedt 1959; Froud-Williams 1985). Malik and Vanden Born (1988) observed that approximately 30% of freshly harvested *G. spurium* seed was able to germinate immediately. Where as, Michiko and Washitani (1992) observed no germination of freshly harvested *G. spurium* seed. Such variable results may in part be attributed to the timing of seed harvest. A study investigating the impact of the date of seed collection on the occurrence of primary dormancy, found that brown *G. aparine* seed harvested before August 1 expressed very high dormancy, whereas, brown seed harvested after August 14 showed nearly 70% germination (Van der Weide 1993). This suggests that the conditions which the seeds are exposed to during the ripening process may also impact the degree of primary dormancy. It has been shown that the quality of light (Red:Far Red) that seeds are exposed to prior to maturation will impact the dormancy state of the seed (Cresswell and Grime 1981; Gallagher and Cardina 1998a). This is likely associated with the activity state of the phytochrome as influenced by the level of chlorophyll within the seed prior to maturity. Cresswell and Grime (1981) investigated the occurrence of primary dormancy in a number of weed species. They observed that small seeded species, which commonly develop a persistent seed bank, often experience a state of primary dormancy that is overcome by a brief exposure to light (Cresswell and Grime 1981). The longevity of the initial dormancy state will vary with species. For *G. aparine,* primary dormancy is significantly reduced after three months of dry storage, suggesting that the initial seed dormancy, if present, is short lived (Van der Weide 1993).

Secondary dormancy refers to a re-induction of dormancy, which occurs after primary dormancy has been released (Benech-Arnold et al. 2000). The occurrence of primary and secondary dormancy allows for dormancy to cycle over time, meaning that a seed can move in and out of dormancy over time. This cycling occurs such that dormancy is released prior to conditions that are favorable to growth and re-induced prior to unsuitable conditions. For cleavers, which is commonly considered a summer annual in Manitoba, dormancy is reduced over the winter allowing for germination during favorable spring conditions and re-induced prior to the onset of winter when seedling survival would be threatened. Under certain conditions cleavers have exhibited a winter annual growth habit. In this case, dormancy is reduced over the summer allowing for germination in the fall. Though it may seem intuitive that dormancy would be binary, such that a seed was either dormant or non-dormant, this is not believed to be the case. Rather, scientists consider seeds to be at some point along a continuum of relative dormancy (Baskin and Baskin 1998b). This means that seeds may be more dormant or less dormant under certain conditions. Differences in the level of dormancy are reflected in the changing temperature range over which germination can occur. For example, under conditions of high dormancy, the range of temperatures that permit germination is quite narrow; whereas, under conditions of low dormancy the temperature range over which germination will proceed is much wider (Benech-Arnold et al., 2000). The varying degree of dormancy is again reflected in the seasonal recruitment patterns exhibited by a species. In temperate climates, where moisture is not generally limiting, seasonal dormancy cycles are considered to be a function of temperature (Benech-Arnold

et al. 2000). However, soil moisture may also be influential, as dormancy has been shown to vary with the water potential of the seed (Benech-Arnold et al. 2000).

In addition to expressing seasonal variation in dormancy levels, some species require a dormancy termination event to stimulate readiness for germination. Such events may consist of fluctuations in soil temperature, exposure to light flashes, changes in soil nitrate concentrations, and/or alterations in the make up of the soil atmosphere. Though information on dormancy mechanisms in weed species is somewhat limited, there have been a number of controlled indoor studies done to investigate the impact of environmental conditions on dormancy.

Studies of the dormancy behavior of *G. aparine* and *G. spurium* have not indicated a requirement for temperature fluctuations to break dormancy. However, there are certain limitations of the temperature ranges within which germination can proceed. This is discussed further in the section on germination behavior.

Investigations of the impact of light on dormancy-break in weed species, showed that seeds of naturally occurring weed populations were stimulated by short "light-breaks" (Wesson and Wareing 1969). The light-break, which lasted for approximately 90 seconds, stimulated a large proportion of the weed species to germinate relative to plots where light exposure was prevented. Light flashes have been shown to stimulate dormancy-break for many weed species. However, the duration, intensity and form of light exposure may have an effect on the species response.

To investigate the impact of light exposure on the dormancy state of *G. spurium,* Malik and Vanden Born (1987c) used a series of controlled growth cabinet experiments. As in the Wesson and Wareing (1969) study, short duration light exposure was shown to

stimulate germination in *G. spurium* (Malik and Vanden Born 1987c). This enhancement effect occurred with exposure periods lasting up to, and including, 36 hours. Continued exposure beyond this period resulted in the imbibed seeds re-entering into a state of dormancy (Malik and Vanden Born 1987c). The results of this experiment indicate that there is a critical period for light exposure of imbibed seed of *G. spurium,* during which dormancy is reduced, but beyond which dormancy is induced. Intermittent light exposure was also found to impact dormancy levels in *G. spurium*. Imbibed seeds exposed to one hour of light during a series of 24-hour cycles showed a 32% reduction in germination when compared to a dark control (Malik and Vanden Born 1987c). No germination took place when seeds were exposed to one hour of light after a 3, 7, or 11 hour period of darkness, when cycled over 8 days (Malik and Vanden Born 1987c). Similar sensitivity to light exposure has been exhibited by *G. aparine.* Sjostedt (1959) observed the highest germination of *G. aparine* seed under dark conditions, with light intensities as low as 20% of full daylight retarding germination. This is supported by Van der Weide (1993) who observed reductions in *G. aparine* germination as a result of 12 hours of light exposure in each 24 hour period.

In addition to the duration of exposure, the sensitivity of *G. spurium* to different light intensities was tested. The results indicate that germination is inhibited by relatively low light intensities ($6\mu Em^{-2}s^{-1}$) when administered over a one week period (Malik and Vanden Born 1987c).

Along with the intensity of the light exposure, the quality of the light itself has been shown to affect germination of *G. spurium*. Green light was found to have a slight stimulatory effect on germination (Malik and Vanden Born 1987c). Whereas, both red

and blue light, are considered somewhat inhibitory (Malik and Vanden Born 1987c). Exposure to far red light resulted in greater inhibition than either red or blue light. However, this inhibitory effect can be overcome by a 2-day dark treatment, prior to light exposure (Malik and Vanden Born 1987c). Inhibition associated with exposure to white light was found to increase with the duration of exposure (Malik and Vanden Born 1987c).

Other factors are likely involved in promoting or hindering dormancy periods in cleavers. One such factor is nitrogen which is present in the soil as nitrate salts. A number of weed species require nitrate in order to terminate dormancy (Benech-Arnold et al. 2000). It is suggested that this requirement may act to promote germination during more favorable periods of the year and in more favorable locations. The rate of mineralization of soil organic nitrogen increases with increasing temperatures resulting in seasonal changes in nitrate concentration. As a result, nitrate sensitive weed species may be triggered to germinate during warmer periods of the year, enhancing their probability of success. However, an experiment conducted to test this theory did not determined a correlation between the emergence period of nitrate requiring weed species and annual nitrogen cycles (Benech-Arnold et al. 2000). Nitrate sensitivity may also enable weeds to colonize spatial gaps, reducing the impact of plant competition. In areas that are free from growing vegetation, the nitrate concentrations are higher relative to areas where plants are established (Benech-Arnold et al. 2000; Dyer 1995). Thus, the germination of nitrate requiring species may be stimulated in vegetation gaps. The germination of both *G. spurium* and *G. aparine* is enhanced in the presence of nitrate (Sjostedt1959; Van den Weide 1993; Malik and Vanden Born 1987c). Dormant *G. spurium* seeds were shown to

germinate after being exposed to nitrate salts, even at low concentrations (1.2×10^{-3} M) (Malik and Vanden Born 1987c). Even though *G. spurium* and *G. aparine* are sensitive to nitrates, germination will not always be stimulated by nitrate salts. Under conditions of prolonged light exposure, the presence of nitrate salts was not shown to induce germination (Malik and Vanden Born 1987c). Thus, the inhibitory effects of light exposure override the stimulatory effects of nitrate salts in *G. spurium* and *G. aparine*.

Oxygen levels in the soil can also affect the ability of seeds to germinate. The concentration of oxygen found within the soil is dependant on the fluctuations in atmospheric conditions, soil porosity (crusting and compaction), soil moisture levels (flooding), the depth within the profile (increase depth, decrease oxygen) and the rate of oxygen uptake by living organisms (Benech-Arnold et al. 2000; Benvenuti and Macchia 1995). In the case of *G. aparine*, oxygen levels between 6-8% are required for germination, with optimum levels being greater than this (Malik and Vanden Born 1988). When exposed to very low oxygen levels over a long period of time, seeds may fall into a state of secondary dormancy, with seed death the ultimate result of prolonged exposure to anoxic conditions (Malik and Vanden Born 1988).

Though experiments have identified certain trends in the mechanisms leading to dormancy-break in *G. spurium* and *G. aparine*, the actual requirements will likely vary among populations and even between seeds themselves (Benech-Arnold et al. 2000). In an *Avena fatua* L. population, it was shown that at any one time the population will consist of a portion of seeds that will readily germinate and some that are dormant. Of the dormant portion, some seeds required nitrates to germinate, some required darkness

and some required both of these factors for germination to proceed (Murdoch 1998). This illustrates the potential variation that may be present in a given weed population.

2.7 Germination

The process of germination is initiated by a series changes within a seed, culminating with the protrusion of the radicle from within the seed (Forcella et al. 2000). The process is often divided into three separate stages; the imbibition phase, the transition phase and the growth phase (Come and Thevenot 1982). During the imbibition phase water from the region surrounding the seed moves into the seed tissue. This is believed to be a passive process, suggesting that it could occur in nonviable, viable and dormant seeds. The point at which the imbibition phase concludes and the transition phase begins is difficult to identify. The transition, or pause phase, is the period during which the metabolic activities essential for germination take place. Hydration is very important during this phase. Osmotic stress may slow or even inhibit germination. The growth phase marks the final stage in germination. It is characterized by the establishment of cellular division and extension, rapid water uptake and ultimately the protrusion of the radicle (Come and Thevenot 1982). Unlike dormancy, weed seed germination characteristics have been studied quite extensively. Most often these studies are conducted under highly controlled conditions, with one or more factors investigated at a time. The most common variables tested are temperature and moisture.

For each weed species, there is a base temperature and moisture level below which germination will not take place. These base levels must first be realized before germination can proceed. Based on germination experiments conducted by Sjostedt

(1959), the optimum temperature range for the germination of *G. aparine* is between 12 and 15 °C. Similar optimums have been identified by Froud-Williams (1985) who observed maximum germination of a hedgerow population at 10 - 14 °C and at 9 - 12 °C for a field population of *G. aparine* (Froud-Williams 1985). Experiments investigating the germination behavior of *G. spurium* showed maximum germination levels at a constant 22 °C, or alternating 10-20 °C, 15-20 °C or 14-24 °C (Malik and Vanden Born 1987b). The optimum moisture range for the germination of *G. aparine* has been identified as being between 40-60% soil water holding capacity (Malik and Vanden Born 1987b). The optimum moisture level suggested for *G. spurium* is between 50 and 80% soil water holding capacity (Malik and Vanden Born 1988). Once germination has begun the temperature and moisture levels will continue to be influential. If moisture availability falls below the minimum level required for germination, the progression towards radicle extension will slow or stop (Oryokot et al. 1997a). The minimum moisture requirement for the germination of *G. aparine* is between 40-50% water holding capacity (Sjostedt 1959). For *G. spurium*, germination was reduced at osmotic potentials below -2.5 bars and prevented at levels below -7.5 bars (Malik and Vanden Born, 1988). Moisture levels beyond the optimum can also be detrimental to germination. For *G. aparine*, Malik and Vanden Born (1988) suggest a maximum moisture level of 80% water holding capacity, after which germination is negatively affected. Temperature impacts on germination are similar to moisture, in that, at temperatures below the minimum requirements germination is slowed. For example, *G. spurium* seeds that were maintained at 4 °C only reached 5% germination after a 3-week period (Malik and Vanden Born 1987b). Increasing temperatures beyond the base level will increase seed

metabolic activity and the rate of germination (Oryokot et al. 1997a). This enhancement effect will only continue up to the optimum temperature value, beyond which further increases in temperature will reduce the rate of germination. Sjostedt (1959) determined that temperatures exceeding 20 °C will begin to inhibit the germination of *G. aparine*.

To date, most researchers have considered temperature and moisture to influence seed germination independently. Meaning that at a moisture level equal to or greater than the base value, both the onset of germination and the rate of germination would be influenced solely by temperature. Based on this concept, the estimated timing of seed germination was focused primarily on the progression of thermal time, often measured as growing degree days (GDD). More recently researchers have recognized the importance of (temperature x moisture) interactions in influencing seed germination. This has lead to the introduction of hydrothermal time for the prediction of germination (Forcella et al. 2000). Hydrothermal time is the product of hydro time and thermal time.

$$\theta_{HT} = (\Psi - \Psi_b) \cdot (T - T_b) \cdot t$$

where θ_{HT} is the hydrothermal time, Ψ_b and T_b are the base water potential and base temperature for germination, and t is time to germination (Roman et al. 1999). Unlike crop species which have been bred for genetic uniformity, weed populations are genetically variable. This variability leads to differences in the response of individuals to environmental conditions. As a result, the germination requirements of individuals of a given weed species will vary. As a result, a germination curve can be produced for each weed species. Generally, weed germination curves have a slightly skewed bell shape when plotted against thermal or hydrothermal time.

Few attempts have been made to investigate germination behavior of weed species under field conditions. This is related to the difficulty associated with characterizing the environmental conditions occurring within a field. Without the ability to make precise measurements of the conditions on a micro-scale, it is difficult to formulate specific conclusions on the relationship of environmental conditions and germination. Though specific relationships may be difficult to decipher in the field, these experiments are particularly valuable in testing the practical significance of relationships identified under controlled conditions.

2.8 Shoot Elongation

The final component of seedling emergence is shoot elongation. This stage represents the period during which the shoot extends from the seed to the soil surface. Unlike germination, studies have shown that shoot elongation is not significantly impacted by soil moisture (Roman et al. 1999). This implies that shoot elongation will proceed even under dry soil conditions. In fact, shoot elongation can continue even under soil moisture conditions that inhibit germination (Roman et al. 1999).

Based on the relationship of soil temperature and shoot growth, this process is considered a function of thermal time. Thus, modeling shoot elongation requires that the base temperatures for shoot elongation be determined. Researchers have found that these values are generally higher than the base values determined for seed germination. In an experiment investigating the base temperature for *Chenopodium album* it was shown that the base temperature for shoot elongation was 3°C higher than that for germination (Roman et al. 1999). A similar relationship was discovered with *Amaranthus* spp.,

where the base temperature for shoot elongation was found to be much higher than for seed germination (Oryokot et al. 1997b). Thus, seed germination and radicle development can occur at lower temperatures than shoot elongation, meaning that radicle development will occur prior to shoot development in spring emerging species. This relationship is of ecological significance, in that, earlier radicle growth ensures that the seedling is securely anchored and ready to access resources which will ultimately be supplied to the newly emerged seedling (Roman et al. 1999; Oryokot et al. 1997b).

Determining the duration of shoot elongation is largely dependant upon the depth at which a seed is located within the soil. For weeds, the position of the seed can be quite variable, and will be impacted by the type of management applied to the field, specifically the intensity of cultivation. Germination on the soil surface is low for cleavers, likely due to the inhibitory effects of light exposure (Froud-Williams et al. 1984). It is generally believed that light can only penetrate the soil up to 1 cm depth (Cussans et al. 1996). However, the penetration depth may vary somewhat depending on the soil clod size. Soils of a very fine tilth (<6mm diameter) reduced light penetration to 2% of that reaching the soil surface after only 0.6 cm depth, with no light penetration reaching 2.5 cm (Cussans et al. 1996). Soils consisting of large clods (26-50mm diameter) allowed light penetration up to 10 cm depth (Cussans et al. 1996). Many studies suggest that *G. aparine* is capable of emerging from depths between 0-10cm (Sjostedt 1959; Froud-Williams 1985). However, some researchers have suggested that seedlings can emerge from seed located 20 cm below the surface (Malik and Van Born 1987b), or even 100 cm below the surface (Froud-Williams et al. 1984). In general, recruitment is less successful when seeds are located on the soil surface or at greater

depths, than in the mid range. Boyd and Van Acker (1993) found that germination was less than 20% of the maximum when *G. aparine* was surface seeded or when seeded at 6-7cm depths. They identified an optimum range of 1 - 4cm depth when soil was maintained at 70 to 75% field capacity. For *G. aparine,* Froud-Williams (1985) suggested an optimum seeding depth of 5cm, with Malik and Vanden Born (1988) sighting a similar range of between 2 and 5cm. For the smaller seeded *G. spurium* a shallower depth is considered optimum (Malik and Vanden Born 1988).

In addition to seed placement impacting the elongation distance, it will also affect the conditions that the seeds are exposed to. Soil temperature and moisture will vary with depth, and depending on the sensitivity of the species, small changes in environmental conditions may significantly impact emergence processes including shoot elongation. In the case of many small seeded broad-leaved species small changes in the burial depth have significantly impacted the probability of successful emergence (Mead et al. 1998). Variation in the extent or timing of emergence associated with the placement of the seed may also result from changing the probability of a seed coming into contact with hazards such as predators (Grundy and Mead 1998). Thus, non-uniform seed distribution will further increase the variation in emergence timing and success as a result of differences in the micro-environment surrounding the seed.

Researchers also have investigated the impacts of tillage and soil type on weed recruitment, by assessing the effect of varying the soil penetration resistance on shoot elongation (Vleeshouwers 1997). In this study, researchers found that the maximum depth from which three weed species could emerge was affected more by the soil penetration resistance than by the soil temperature. This suggests that soil penetration

resistance may be of greater importance to shoot elongation than was originally considered. This is emphasized again in a study by Van der Weide (1993), where it was shown that the impact of moisture on *G. aparine* emergence was affected by the resistance of the soil. In this experiment the rate and extent of emergence associated with low soil moisture levels was reduced to a greater degree when soil resistance was high (Van der Weide 1993).

2.9 The Impact of Tillage on Seed Germination

Recruitment is defined as the process comprised of both the germination and emergence of a seed. Weed seedling recruitment is highly dependant upon the conditions of the soil environment. These conditions are influenced by a number of different management practices including cultivation, crop rotation and fertilization. Though many of these practices impact soil conditions, cultivation is believed to have the greatest influence on factors affecting weed seedling recruitment.

A number of researchers have investigated the effects of tillage intensity on weed community structure and seed germination (Arshad et al. 1995; Botto et al. 1998; Chancellor 1985; Chepil 1946; Derksen et al. 1993; Dyer 1995). From this, researchers have speculated that the intensity of tillage would impact the make-up of the weed community in a predictable way. It has been suggested that under reduced tillage conditions perennial dicot species, annual and perennial grasses, wind-disseminated species, and volunteer crops would increase, and annual dicot weeds would decrease (Froud-Williams et al. 1981). However, studies investigating this theory indicate that such predictions may be oversimplifications. Rather, weed community structure is

dependant upon the original species present, the environmental conditions, herbicide use, crop rotation, as well as, the tillage practices used (Derksen et al. 1993; Gill and Arshad 1995; Légère and Samson 1999). Thus, the relationship of tillage intensity to weed community structure is more complex than originally thought. Though tillage intensity is one of a number of factors influencing the structure of weed communities, it can significantly impact the success of seedling recruitment by affecting the environment that weed seeds are exposed to.

The seedling recruitment microsite is defined as all of the abiotic and biotic variables directly surrounding a seed (Harper 1977). Tillage influences the microsite in two main ways; first by altering the soil structure and surface residue levels, which can affect soil temperature, soil moisture, nutrient levels and the penetration resistance of the soil, and second by changing the vertical or horizontal placement of the seed, including short term surface exposure (Chancellor 1985; Wesson and Wareing 1969).

2.10 Soil Properties Influenced by Tillage Intensity

2.10.1 Soil Bulk Density

Tillage operations act to disturb the soil in the upper profile, resulting in soil structural changes. These changes are often measured as differences in the soil bulk density. A number of experiments have shown that the bulk density of soil within the cultivation zone is different from that within the same zone in uncultivated soils (Potter et al. 1985; Kettler et al. 2000; Xu and Mermoud 2001). However the relationship between bulk density in tilled and untilled plots can be variable. For example, Kettler et al. (2000) found that long term no-till soils have lower bulk density at the 0 to 7.5cm depth than

cultivated soils. Where as, Xu and Mermoud (2001) found that the bulk density of uncultivated soils was greater than that of cultivated soils when measured to a depth of 40cm. Research by Potter et al. (1985) showed no significant differences in bulk density measured between 2.5cm and 10cm among three tillage treatments; no-tillage, chisel plow and conventional tillage (moldboard plow and disking) after three treatment years. The discontinuity in the relationship of soil bulk density to cultivation intensity may be associated with variability in soil type, organic matter level, cropping system and/or climate. Differences may also be associated with incongruent experimental procedures including, the difference in the depth of the bulk density measurement. The differences in bulk density associated with changing depth may be greater than differences generated by varying tillage.

Bulk density is also in part, associated with changes in the soil pore-size distribution. In general, tillage is believed to increase the percentage of large sized pores (>50 μm) relative to small pores (<10 μm) (Xu and Mermoud 2001; Blevins and Frye 1993). The extent of this difference may vary according to the intensity of the tillage operation. For example, Xu and Mermoud (2001) showed that the pore size distribution of soils that underwent subsoiling tillage (subsoiler and rotary cultivator) was significantly different from those that were conventionally tilled (rotary cultivator) or left untilled. No significant differences were present between the conventional and no-tillage treatments. However, this experiment was conducted over a single year, suggesting that structural changes associated with differing tillage intensity may not have had enough time to develop.

Pore size distribution impacts the water infiltration rate and thus affects the moisture profile of the soil. Blevins et al. (1983) showed greater saturated hydraulic conductivity in no-tilled soils relative to tilled soils due to better pore continuity and enhanced earthworm activity. However, Xu and Mermoud (2001) found that the rate of infiltration is greater in conventionally tilled soils relative to untilled soils. This is attributed to increased surface roughness and a higher proportion of large pores and gaps in tilled soils. However, with the absence of substantial residue cover these soils may also be more prone to surface crusting associated with raindrop impact. Crusting will increase water runoff, reduce the oxygen concentration in the soil and increase the surface soil resistance (Blevins and Frye 1993; Benech-Arnold et al. 2000). Cultivated soils also tend to have higher drying rates than untilled soils. Thus, even though conventionally tilled soils may have a higher infiltration rate the overall water retention is generally greater in untilled soils (Azooz and Arshad 2001; Johnson et al. 1984).

Bulk density and pore size distribution measures can also indicate the level of compaction of a soil. However, this is more directly measured by determining the penetration resistance of the upper soil layer. Compaction can affect recruitment by impacting the rate of diffusion of gases within the soil environment, including oxygen, carbon dioxide and ethylene. In turn, the composition of the soil atmosphere can affect seed dormancy and germination (Baskin and Baskin 1998b). In particular, oxygen concentrations in the soil atmosphere are important, as oxygen is one of the necessary components for germination to proceed. Though oxygen levels in the soil rarely go below 19%, under crusting or flooded conditions oxygen concentrations may drop below 10% and 1%, respectively (Benech-Arnold et al. 2000). In an experiment investigating

the impact of compaction on oxygen concentration on an untilled plot, Topp et al. (2000) found that the oxygen concentration was reduced in soils that were compacted. This is associated with a reduction in the rate of both the diffusion of oxygen to the seed, and the diffusion of toxic fermentation products away from the seed within compacted soils (Benvenuti and Macchia 1995). However, the oxygen concentration limits within which germination is possible depend upon the species considered. In the case of *G. aparine*, oxygen levels below 6-8% significantly limit germination (Malik and Vanden Born 1988). In addition to affecting the soil atmosphere, the extent of soil compaction will affect the rate at which the primary root and shoot move through the soil. Malhi and O'Sullivan (1990) determined that the penetration resistance of untilled soils was greater than those that were conventionally tilled. Based on measurements at four different sites, the depth to which soils were compacted under no-till ranged from 3.5cm to 10.5cm (Malhi and O'Sullivan 1990). Compaction will impact recruitment differently depending on the sensitivity of the species considered. For example, increasing soil impedance reduced the emergence of calabrese (*Brassica oleracea* L. Italica Group), carrot (*Daucus carota* L.), onion (*Allium cepa* L.) and sugar beet (*Beta vulgaris* L.), as a result of restricted shoot elongation after germination (Vleshouwers 1997). In the case of cleavers (*G. aparine*) the time to emergence of seeds placed at 2cm depth varied from 70 to 120 degree-days when the soil resistance was varied between 1.5 and 10 kg/cm^2 (van der Weide 1993). The recruitment response of weed species to penetration resistance may vary with seeding depth. When using pre-germinated seeds Vleeshouwers (1997) found that the interaction of penetration resistance and depth significantly affected the rate of emergence of *Polygonum persicaria* L.. This however, was not the case for

Chenopodium album L. where the seeding depth at a given resistance showed no effect on the rate of emergence. Thus the relationship will vary with species. In the case of cleavers, Van der Weide (1993) showed that increasing the soil resistance resulted in a decrease in the depth from which cleavers germination was successful. At low soil resistance (1.6 kg cm^{-2}) germination occurred from 10cm depth, where as, at a high soil resistance (10 kg cm^{-2}) germination was restricted to shallower depths.

2.10.2 Soil Moisture

In general, soils that are tilled are believed to be drier than soils that are not tilled. In an experiment investigating the impact of tillage systems on soil moisture, soil moisture levels within the 0 – 10cm depth tended to be higher in untilled plots relative to conventionally tilled plots (Arshad et al. 1995). An experiment using soil filled columns found that soil moisture levels were 10% higher in the untilled columns relative to the tilled columns when the measurements were taken 23 hours after cultivation (Moroizumi and Horino 2002). Blevins et al. (1971) also found greater soil moisture in no till plots relative to conventionally tilled plots down to 60cm depth, with the greatest differences in the 0 – 8cm zone. Average spring moisture levels taken from 0 - 15cm depth were significantly higher in untilled plots relative to tilled plots in three of five years (Malhi and O'Sullivan 1990). This difference was primarily attributed to the snow catching ability of stubble and increased melt water entering the untilled plots. Growing season volumetric soil moisture measured at four depth intervals (0-15cm, 15-30cm, 30-45cm, 52.5-67.5cm) showed that no-till soils were consistently wetter than tilled soils (Arshad

and Azooz 1996). This difference in moisture levels may have been due to increased surface roughness and enhanced potential evaporation as a result of cultivation.

The presence of residues on the soil surface are generally linked to increased soil moisture throughout the growing season as a result of reduced evaporation and increased infiltration in the upper soil layers (Blevins et al. 1971). Plant residues act to shade the soil surface from solar radiation, insulate the surface from warm air, and limit water vapor movement from the soil to the air (Blevins and Frye 1993). Residues also protect the soil surface from the compacting forces of raindrops, and reduce surface water runoff (Blevins and Frye 1993). Though moisture conservation associated with residues takes place throughout the growing season, it is most effective early in the season when water loss is primarily by evaporation rather than transpiration. Though higher residues are often associated with higher soil moisture levels, the results of experiments investigating the influence of tillage (residue management) on soil moisture have varied. Potter et al. (1985) did not observe any difference in volumetric soil moisture within the 2.5-15cm depth for conventional tillage, chisel plow and no-till with an average residue cover of 7.4%, 37.6% and 66.2% respectively.

The impact of tillage on soil moisture is also influenced by soil properties including the soil organic carbon levels. For example, when the level of organic carbon present within the soil is high, Pires da Silva et al. (2001) found that the drying effect of tillage was reduced. This suggests that the water holding capacity of the organic matter is compensating for the water loss often associated with cultivation. However, cultivation can lead to a reduction in the soil organic carbon levels near the surface due to increased mixing and decomposition (Blevins et al. 1983). Thus, the prolonged use of tillage will

likely result in a reduction in the organic carbon level within the soil, leading to a reduced water holding capacity.

Roberts and Potter (1980) recognized the importance of soil moisture on seedling recruitment. In an experiment investigating the impact of temperature, cultivation and rainfall on seedling recruitment in the field, results suggested that seedling emergence patterns initially related to changing temperatures in the spring and then largely coincided with rainfall events. Based on their studies, Roberts and Potter (1980) suggested that the influence of temperature changes and precipitation events on the overall seedling emergence pattern was greater than that of other factors, including cultivation. This is not to imply that tillage intensity and the resulting impact on the seedling recruitment microsite will not influence seed germination, but rather, that there are factors that may override the influence of tillage under some circumstances. In the Roberts and Potter (1980) experiment, cultivation was achieved by mixing the soil with a garden fork to a depth of 10 cm. This form of "tillage" may not have been intense enough to lead to dramatic changes in soil structural properties or seed placement. Thus, the simulated tillage used in this experiment may not accurately represent the impact of field scale cultivation on factors affecting seedling recruitment. As a result, the outcomes of this experiment should be interpreted with caution.

2.10.3 Soil Temperature

The temperature of a soil is dependant upon a number of factors including, for example, ambient air temperature, intensity of solar radiation, surface cover and various soil properties. Differences in soil temperature are also related to the amount of moisture

present within the soil. Initially, the wetting of dry soils will lead to an increase in the rate of heat transfer from the air to the soil, as a result of increased conductivity. Tillage can influence thermal conductivity by affecting soil porosity and/or the soil moisture level. For example, decreasing soil porosity or increasing the soil water content will increase the thermal conductivity (Potter et al. 1985). However, there are limits to this relationship. It is believed that thermal conductivity is maximized at volumetric water contents between 8 and 20% (Arshad and Azooz 1996). Increasing soil moisture beyond this level will often lead to a reduction in the rate of heat transfer, as more energy is required to increase the temperature of water relative to soil particles or air. In an experiment investigating temperature in irrigated and non-irrigated soils Burke and Upchurch (1995) found that non-irrigated soils warmed faster and had a higher average temperature than irrigated soils. This was an example of the effect of the higher heat capacity of water relative to soil particles and air. Thermal conductivity and the volumetric heat capacity are both important in defining soil thermal diffusivity. Soil thermal diffusivity is directly proportional to the thermal conductivity and inversely proportional to the volumetric heat capacity. This measure is used to indicate the type of response a soil will have to energy additions or subtractions. A soil with low diffusivity will not transfer energy rapidly, and as a result it will likely experience more extreme fluctuations in temperature within a relatively thin layer of soil. A soil with a high diffusivity will transfer energy more efficiently, and as a result added energy will move rapidly through the profile, thus muting temperature extremes. In a study conducted in a semiarid region of British Columbia researchers found that the soil thermal diffusivity was generally higher in tilled plots relative to untilled to a depth of 67.5cm (Arshad and

Azooz 1996). However, this result occurred in only one year of the two year study. In the second year, there was no difference in the thermal diffusivity between the tilled plots and the untilled plots to a depth of 45cm. Potter et al. (1985) found that untilled plots had a higher thermal diffusivity than conventional or chisel plowed plots. This suggests that untilled soils will tend to exhibit less extreme temperature ranges in the upper soil profile relative to tilled soils. A number of experiments have shown that conventionally tilled plots tend to reach greater spring maximum temperatures, relative to zero tilled plots (Bullock and Lafond 2002). The difference in the minimum temperatures is generally much less than what is observed for the maximum temperature. Field measurements showed that the maximum summer soil temperature at 5cm was significantly greater in the tilled plots relative to the untilled (Bullock and Lafond 2002). However, the minimum temperature was actually significantly lower in the untilled plot relative to the tilled plot (Bullock and Lafond 2002). When average temperatures are considered, tillage was shown to increase the average daily temperature by 1.6 °C on the surface and 1.0 °C at 4cm depth (Moroizumi and Horino 2002). Temperatures at 10cm depth were on average 1.1 lower in no-till plots relative to tilled plots (Cox et al. 1990). The temperature difference between tilled and untilled columns was observed up to 24cm depth (Moroizumi and Horino 2002). A similar relationship was observed by Malhi and O'Sullivan (1990), where the average soil temperatures at 2.5cm and 5cm depth were; 12.9 °C and 10.6 °C (zero till) and 15.7 °C and 11.7 °C (conventional tillage), respectively.

2.11 The Impact of Seed Movement as Influenced by Tillage Intensity

The degree to which seeds are moved by tillage will vary with the form of tillage implement used. No-tillage cropping systems tend to leave the majority of weed seeds on the surface or within the top 1cm of the soil profile (Dyer 1995). Seeds that remain on the soil surface are exposed to solar radiation which can induce dormancy in certain species, including cleavers (Malik and Vanden Born 1987c). Depending on the dormancy-break requirements of the species, extreme temperature and moisture fluctuations associated with the soil surface, may also influence dormancy behavior (Baskin and Baskin 1998b). However, surface placement does not necessarily limit recruitment, for some species including cow cockle (*Saponaria vaccaria* L.), recruitment is more successful when seeds are exposed to surface conditions. In an experiment investigating the germination of 16 annual and perennial weed species, *S. vaccaria* reached 82% germination ten days after planting when seeded on the surface (Boyd and Van Acker 2003). For this species, this level of germination was greater than at any other depth investigated.

Moldboard plowing leads to a uniform distribution of seeds located deep within the soil profile (Dyer 1995). The depth of plowing can be quite variable; 18 - 20cm (Botto et al. 1998), 25 - 30 cm (Gallagher and Cardina 1998b). In a simulation experiment using clay beads, 50-60% of the recovered simulated seed were found within 11 to 16cm depth after moldboard plowing (Yenish et al. 1996). This form of inversion tillage is often used as a weed control technique. The absence of diurnal temperature fluctuations or low oxygen concentrations at depth may prevent dormancy-break from occurring. As a result, seeds often die and decompose prior to germination, depending on

the seed longevity and the dormancy behavior of the weed species. Under conditions where germination does occur at depth, energy stores within the seed must be sufficient to allow for the shoot to extend to the soil surface, otherwise the seedling will die.

Chisel plowing distributes the majority of seeds at an intermediate depth (Dyer 1995). In the Yenish et al. (1966) experiment, 40% of the recovered simulated seed were found within 4cm of the surface. Generally, germination is believed to be greatest at intermediate depths. In the Boyd and Van Acker (2003) study, six of the ten annual weed species seeded at depths between 1 and 7cm, expressed germination levels greater than or equal to 70%, nineteen days after planting.

The form of tillage implement used will impact the position of the seed within the soil profile. This is important because soil conditions vary spatially, both vertically and horizontally. As a result, tillage can impact the microenvironment that seeds experience by changing the position of the seed within the soil profile. The tillage can induce the movement of seeds both vertically and horizontally. However, it is movement along the vertical plane that is of primary interest when considering conditions that influence seed dormancy, germination and emergence. Generally, the factors that are considered influential in weed seedling recruitment are; the occurrence and duration of light exposure at the soil surface, soil temperature conditions, and soil moisture levels.

2.11.1 Light Exposure

In knowing that short periods of light exposure can promote germination in positively photoblastic seeds, scientists have investigated the impact of light flashes during tillage operations on weed seed germination. In one such study, day verses night

cultivation was investigated in combination with other factors including cropping history, tillage implement, and post cultivation light exposure (Botto et al. 1998). The results showed that daytime tillage stimulated higher weed germination for two fields in the late winter and one field in the late summer. During these periods, daytime tillage increased germination by a factor of 1.5 to 2 over night-time tillage (Botto et al. 1998). However, the magnitude of the response varied from field to field and from season to season within a field (Botto et al. 1998). Thus, the relationship between light flashes and germination was not consistent over time and space. In similar studies, researchers again found that the light flash associated with cultivation resulted in greater weed germination (Gallagher and Cardina 1998b; Arshad et al. 1995). However, like in the Botto et al. (1998) study, this relationship was not observed under all conditions. Thus, generalizations should not be made regarding the impact of light flashes on weed germination. Rather, germination response will vary with season and species, according to the emergence periodicity and the particular light sensitivity of the species.

The impact of dormancy cycles is illustrated by a study investigating the germination response of common knotweed *Polygonum aviculare* L. to tillage (Roberts and Potter 1980). *P. arviculare*, which exhibits a spring emergence periodicity, responded with high emergence when tillage was applied in March or early April. However, when tillage was applied later in the season very little emergence resulted (Roberts and Potter 1980). Thus, the influence of the emergence periodicity of a weed species will likely override the potential for germination associated with a light stimulus. In the case of cleavers, the emergence of North America populations is concentrated in the spring season, with minimal emergence in the fall (Malik and Vanden Born 1997b).

In Europe, emergence is primarily in the fall season, with minor emergence taking place in the spring (Froud-Williams et al. 1984). Cleavers, which have been shown to exhibit a germination response to light flashes, may be stimulated to germinate by cultivation (Malik and Vanden Born 1987c). However, the germination response is also influenced by other factors including the soil temperature, soil moisture, duration of the light exposure and the initial dormancy state of the seeds.

As a result of the influence of other environmental factors, cultivation may not lead to increased weed germination, even when light sensitive species are present. Under limiting conditions (low moisture, high temperature) or ideal conditions, the anticipated stimulation effect of short duration light exposure may not occur, or may be delayed. The impact of low moisture levels was illustrated in an experiment investigating seedling emergence as influenced by tillage and rainfall events (Roberts and Potter1980). In this study, weed seedling emergence was greater where soils were cultivated relative to where they were left undisturbed. However, the emergence response to cultivation did not always take place immediately after cultivation. For example, after a June cultivation operation, the anticipated flush of weeds was delayed due to extremely low soil moisture levels. Emergence was restricted until moisture levels were sufficient for germination, resulting in a flush of weeds four months post cultivation (Roberts and Potter 1980). Even under conditions that do not appear to be restrictive, cultivation may not produce a germination effect. In the Botto et al. (1998) study, weed seedling emergence stimulated by chisel plowing was similar for both daytime and night-time tillage. This implies that factors other than light exposure led to the weed emergence that took place. Some researchers have speculated that light reaching the soil surface after cultivation acts to

stimulate germination, even when fields are cultivated in the darkness. An experiment using transparent and opaque coverings was used to investigate this theory (Botto et al. 1998). Plots were cultivated at night and then covered with either of the materials. The resulting germination levels were not different between the two cover treatments, suggesting that there is no effect of post cultivation light exposure on seed germination (Botto et al. 1998). Thus, it is difficult to predict the importance of light flashes associated with cultivation on weed emergence. According to the studies by Roberts and Potter (1980) light exposure associated with cultivation is not a significant factor influencing weed seed germination.

2.11.2 Vertical Soil Temperature Variation

Due to the unique properties of soil, temperature levels can vary significantly with relatively small changes in depth. Unfortunately, access to data supporting this relationship is uncommon, as very few experiments consider fine spatial scales when measuring differences in soil temperature. However, in an experiment by Malhi and O'Sullivan (1990), fine scale soil temperature measures were obtained. Field measurements of the soil temperature in May recorded at two depths (2.5cm and 5cm) showed an average difference of 2.3°C and 4.1°C for zero-till and conventionally tilled plots, respectively (Malhi and O'Sullivan 1990). In this case, the average temperature at 2.5cm was higher than at 5cm (Malhi and O'Sullivan 1990). However, the relationship of soil temperature changes over depth will depend on the sampling period considered. Bullock and Lafond (2002) observed that for both tilled and untilled plots, the mean soil

temperature at 5cm was warmer than at 40cm for the period between April and September. However, this relationship was reversed for the remainder of the year.

In addition to differences in the average temperatures at depth, the amplitude of temperature fluctuations also varies spatially. Reimer and Shaykewich (1980) measured soil temperature fluctuations at 1, 10, 50, 100 and 200cm depths. Using 5-day averages, they observed a reduction in the magnitude of temperature fluctuations from 1 to 200cm. Thus, the amplitude of temperature fluctuations becomes increasingly muted with depth.

2.11.3 Vertical Soil Moisture Variation

Studies have shown that soil moisture levels vary with depth. Based on a one day sampling period, Malhi and O'Sullivan (1990) recorded differences in the gravimetric soil moisture at three depths; 0 – 15cm, 15 -30cm and 30 – 60cm. In this study, the gravimetric soil moisture was greatest at (0 – 15cm) moderate at (15 -30cm) and lowest at (30 – 60cm) (Malhi and O'Sullivan 1990). However, this relationship will vary depending on the time of sampling in relation to rainfall events and the water holding capacity of the soil as determined by the soil texture and organic matter content. Fluctuations in soil moisture are more extreme on the surface and within the upper soil depths as a result of the direct wetting and drying cycles associated with rainfall events, the impact of vegetation cover and solar radiation. Moisture fluctuations will become muted with depth, given no below ground recharge.

2.12 Temporal Variation in Soil Conditions

Environmental conditions within the soil vary not only with disturbance and within space, but also over time. This is important when locating the recruitment microsite for a given species, because the vertical position of this microsite will vary over time. Variation in soil temperature and moisture can occur over many temporal scales, from very fine to quite coarse. Over a 24 hour period the difference between the maximum and minimum temperature at 5cm was shown to be over 20 °C when measured in July (Burke and Upchurch 1995). Due to the difficulties associated with measuring accurate changes in soil moisture over short periods, this form of information is lacking in the literature. However, one would expect that soil moisture levels would also vary over short time periods, especially under conditions of wetting associated with rainfall and drying associated with solar radiation. Soil moisture and temperature will also vary over a season based on the time of year and the temporal proximity to rainfall events. Du Croix Sissons et al. (2000) demonstrated that the conditions in the soil will vary with time. In this experiment, the recruitment depth for five different weed species varied from the preseeding to the prespray period. This difference was attributed to the combined effects of soil structural differences resulting from the seeding operation and changing seasonal conditions.

2.13 Summary and Objective

Tillage has been shown to directly affect soil physical properties, including soil bulk density, pore size distribution and organic carbon levels. This in turn influences soil moisture, soil temperature, the aeration status and nutrient conditions experienced by

seeds. Tillage also affects the placement of seeds on or within the soil profile. Measurements have shown that soil temperature and moisture conditions vary with depth. As a result, tillage indirectly affects the microsite conditions that seeds are exposed to by affecting their placement. The impact on weed seedling recruitment of the changes in the soil physical properties and seed placement associated with tillage operations will vary according to the specific recruitment requirements of the weed species considered. Cleavers (*G. spurium*) germination has been shown to exhibit certain sensitivities to factors that can be influenced by the intensity of the tillage operation used. This includes a sensitivity to light exposure that suggests that recruitment would be less successful on, or near, the soil surface. This in turn leads to the speculation that recruitment of cleavers seedlings will be lower under a no-till situation relative to a conventionally tilled situation.

The objective of this study is to determine changes in the microsite conditions associated with varying the tillage intensity and to what extent tillage and the concomitant changes in the microsite conditions impact the recruitment of cleavers (*G. spurium*).

CHAPTER 3

Materials and Methods

3.1 Cleaver Seed Collection and Characterization

In February, 2001 cleavers seed was sourced from a seed cleaning company (Brett-Young Seeds Ltd. Winnipeg, MB). The seed was received in the form of mixed screenings from cleaning operations. The seed mix was primarily that of weed seeds, with cleavers being the predominant species. The mix represented a composite of screenings from a number of fields distributed through-out the Prairie Provinces (MB, SK and AB). After separating the cleavers seed from the remaining screenings, the dry seed was stored in a closed container at a constant temperature of 4°C.

3.1.1 Species Identification

To determine the species make-up of the cleavers seed used in this experiment, a subsample was sent to Dr. Suzanne Warwick (Agriculture and Agri-Food Canada; Ottawa, Ontario) for chromosomal analysis. Based on methods as described by Dolezel (1991), flow cytometry was used to separate the two species based on ploidy levels as indicated by the amount of genetic material present in the cells. Known samples of *G. aparine* and *G. spurium* seed were obtained from Herbiseed seed suppliers (Twyford, England). The DNA content of five leaf samples of each of *G. spurium*, *G. aparine* (German spring germinating) and *G. aparine* (British fall germinating) was measured using a Ploidy Analyzer PA (Partec, Münster, Germany). From the Brett-Young Seeds Ltd. seed lot, nine plants were grown out and the DNA content of tissue samples from

each plant was measured. The DNA content of the Herbiseed check samples was compared to that of our samples. A near match in the DNA content was considered a positive identification. In addition to the work done by Dr. Warwick, five plants were identified by directly counting the chromosomes of mitotic cells.

A random sample of seeds from the seed lot obtained from Brett-Young Seeds Ltd. was planted and grown out in a greenhouse. Root tips from these plants were harvested in the morning (8:00-10:00am CST) and placed in glass vials filled with distilled water. Vials were stored in an ice water bath kept in a refrigerator for 24 hours. After the 24 hour pretreatment, the distilled water in the vials was replaced with Carnoy's solution I fixative (Singh 1993). Roots were refrigerated in the fixative for between 15 and 24 hours. After fixation, roots were washed with distilled water and placed in vials containing approximately 1ml of 10% HCl. The vial was then placed in an oven at 60 °C for 10 minutes. After hydrolysis, roots were stained using Feulgen stain, and slide preparations were made as described by Singh (1993). Individual cells were observed using a dissecting a microscope. Identification of the species was based on the number of chromosomes present in cells arrested at metaphase.

3.1.2 Seedlot Germination

The germinability of the cleavers seed was determined under controlled conditions. Fifteen petri dishes were lined with two layers of Whatman #1 filter paper. Thirty cleavers seeds were placed in each petri dish and the filter paper was wetted with approximately 3.5ml of a 0.1% solution of KNO_3. The plates were maintained in darkness at alternating 16 hour day/8 hour night temperature of 17°C/22°C.

Approximately every two days supplemental KNO_3 was added to the plates until approximately 0.5ml of free fluid was visible when the plates were tipped to one side. Germination was indicated by the visible protrusion of the radicle from the seed. Germinated seeds were counted and recorded every two to three days until no further germination occurred. This experiment was repeated one time.

3.1.3 Impact of Simulated Seasonal Transition on Seed Germination

A controlled experiment was conducted to determine how temperature changes associated with winter-spring and summer-fall seasonal temperature transitions impacted the germination of cleavers seed. Pretreatments were applied to dry cleavers seeds which were maintained in darkness. Two subsamples of cleavers seed were pretreated under differing conditions. One pretreatment was created to simulate an over-wintering period. This consisted of a cold temperature treatment; run 1 and 2 at a constant -22 °C, run 3 and 4 at a constant -8 °C. The second pretreatment was designed to simulate a summer period. This consisted of a warm temperature treatment; all four runs at a constant +20 °C. Seeds remained in the pretreatment for approximately one month. After this, the pretreated seeds were sterilized and plated.

To sterilize the seeds, they were submerged in a 10% v/v bleach solution. The seed-bleach mixture was stirred for 10 minutes, after which the seeds were rinsed three times in distilled water. After sterilization, the moist seeds were covered with aluminum foil to avoid significant light exposure. Thirty seeds were placed in a petri dish lined with two layers of Whatman # 1 filter paper. Plates were then moistened with approximately 3.5ml of either distilled water or a 0.1% solution of KNO_3. Fifteen

replicates per run were prepared for each combination; cold pretreatment and H_2O, cold pretreatment and KNO_3, warm pretreatment and H_2O and warm pretreatment and KNO_3. Prepared plates were placed into one of two opaque rubber containers, each of which was covered by a shade cloth bag to eliminate light seepage into the boxes. A StowAway Tidbit (Onset Computer Corporation Bourne, MA) temperature recorder was placed inside each box in runs 1, 2 and 3. Boxes were placed into temperature controlled germination cabinets. Those seeds which were exposed to a cold pretreatment were placed in warm cabinets (run 1 at 17-22°C, run 2 and 3 at 17-24 °C) and those seeds which were exposed to a warm pretreatment were placed in cold cabinets (run 1 at 10-15°C, run 2 and 3 at 8-15°C). Germination counts were done every two to three days, at the same time additional distilled water KNO_3 was added until approximately 0.5ml of free fluid was visible when the plates were tipped to one side. Counts took place in a dark room using a green safe light (filter wavelength 500-570, 40 watt incandescent bulb) which is not considered inhibitory to germination (Malik and Vanden Born, 1987). Germination was defined as the point at which the radicle first became visible on any given seed.

Light seepage into the boxes was measured using a model LI-1000 Quantum Sensor. This was tested in a room lit by fluorescent light. The point sensor was inserted into the boxes which were then closed and placed within the shade cloth bags. No light was detected by the sensor, suggesting that the light seepage was less than $0.00417\mu molm^{-2}s^{-1}$. This light level is not considered inhibitory to cleavers germination (Malik and Vanden Born, 1997)

3.2 Cleavers Seedling Recruitment as Influenced by Tillage

3.2.1 Site Description and Background

In 2001 and 2002, field experiments were conducted at two sites within the Interlake Plain Ecoregion of Manitoba. Sites were located approximately ten miles apart, with one near Petersfield, MB at SW1-16-3E and the other near Komarno, MB at NW27-17-3E.

The Petersfield site was situated on a Gleyed Dark Grey Chernozemic soil (Typic Argialboll). This clay soil consisted of approximately 18% sand, 16% silt and 66% clay in the upper profile. The soil pH and organic carbon content in the upper profile was approximately 6.3 and 1.4% respectively (Pratt et al. 1961).

Prior to the start of the trials, the field was conventionally tilled and cropped to barley in the summer of 2000. Nitrogen fertilizer was last applied to the field in the 1999 cropping season. Cultivation of this field last occurred in the fall of 2000, and was accomplished using a sweep cultivator and heavy harrows. No additional tillage operations were conducted before the start of the trial in the spring of 2001. Barley stubble was present on the soil surface in the spring of 2001.

The Komarno site was situated on a Gleyed Rego Black Chernozemic soil (Aquic Haploboroll). This silt loam soil consisted of approximately 30% sand, 50% silt and 20% clay. The soil pH and organic carbon content in the upper profile was approximately 7.5 and 2.7% respectively (Pratt et al. 1961). Prior to the start of the trial, the field was conventionally tilled and cropped to canola in the summer of 2000. Nitrogen fertilizer was last applied to the site by the producer in the spring of 2001. Tillage with a sweep cultivator was performed once on June 4, 2001, just prior to the start of our research trial.

In the spring of 2001, the overall % residue cover at each site was estimated visually. In the spring of 2002, surface photographs were taken of the plots originating in 2001 in order to determine residue cover. A single picture was taken of the surface in each control and high density cleavers subplot within each tillage treatment replicate. This resulted in 54 pictures taken per site. The camera was mounted on a frame located approximately 1m above the soil surface. In order to estimate residue cover from the pictures a template was designed to select a 0.25 m^2 area from within each photo. The template consisted of a square grid within which 50 random intersection points were selected. The calculation of % residue cover was based on the number of times that one of the fifty selected intersection points fell upon a piece of stubble. Stubble cover was estimated for each tillage treatment based on the analysis of a picture from one subplot within four randomly selected tillage replicates. This was done for both the augmented and non-augmented treatments (See 3.2.2).

3.2.2 Tillage Intensity and Cleavers Recruitment

The same methods were used at both sites unless otherwise specified. For a description of the field events please refer to Appendix A, Table 1 and Figure 1. The field experiment included three tillage treatments; no additional tillage for the duration of the experiment (T0); one fall tillage operation only (T1) and both spring and fall tillage (T2). Two cleavers seeding densities were included; a moderate seeding density (250 seeds m^{-2}) and a high seeding density (1000 seeds m^{-2}). Recruitment of one other weed species, volunteer canola, was also considered (spring 2001 experiment only). Volunteer canola was seeded at a single density (115 seeds m^{-2}). Control subplots, which did not

receive any supplemental weed seeds, were also maintained. At the Komarno site, space restrictions limited the number of treatments; as a result, the low density cleavers and the canola treatments were not included at this site.

Treatments were arranged using a split-plot design, with a randomized complete block of the mainplots. Mainplots were tillage treatments, which measured 8.5m by 11m and 7.5m by 5m in Petersfield and Komarno, respectively. These plots were blocked to account for topographic variation at both sites in both years. Seeding treatments made up the 2.5m by 2m subplots contained within each mainplot. At each site the mainplots were replicated nine times, forming nine blocks. In 2001, the sites consisted of nine mainplot blocks representing a total of 180 and 54 subplots, in Petersfield and Komarno, respectively. Two 10m alleyways were included to facilitate the movement of machinery, specifically the tractor and cultivator. Smaller (0.5m) alleyways were located in between subplots to allow for movement around them. In 2002, experiments were repeated at both Petersfield and Komarno. The mainplot tillage treatments included; no additional tillage for the duration of the experiment (T0); one fall tillage operation only (T1) and both spring and fall tillage (T2). The subplot seeding treatments included only the high density cleaver treatment (1000 seeds m^{-2}) and the control. Thus, in 2002 the experimental plots were of equal size at both sites, each comprised of nine 7.5m by 5m mainplot replicates with six, 2.5m by 2m subplots per mainplot. Though T1 treatment plots were included in the 2002 experimental plots, the treatment was subsequently dropped from the experiment in this year.

Prior to applying treatments in 2001, seedbank samples were taken using an 8.5cm diameter cylindrical sampler. Sampling was done to a depth of 8cm. Three soil

cores were taken from each subplot and bulked. These samples were placed in greenhouses which were maintained at approximately 20 °C. The samples received water as needed. Emerged seedlings were identified and removed. Once no further emergence was observed the soil samples were placed in a -20 °C freezer. Samples were maintained under these conditions for approximately one month. After this period, samples were again put in greenhouses where weed emergence was observed and recorded.

After seedbank sampling, the Petersfield plot was sprayed on May 26, 2001 with glyphosate at 1350 g a.i. ha^{-1}. This was accomplished using an ATV sprayer equipped with a 3m wide boom and six standard 11001VS TeeJet nozzles (TeeJet Mid-Tech Northwest, Uniontown, WA). The nozzle pressure was at 275 kPa resulting in the application of 54 L ha^{-1} of spray solution. Because cultivation was done at the Komarno site in the spring of 2001, spraying with glyphosate was not necessary. On May 27, 2002, both sites were sprayed with glyphosate at 1350 g a.i. ha^{-1}.

In the spring of 2001, a mix of weed seed (cleavers or canola) and sand was spread by hand onto designated plots after the glyphosate had been applied. In the spring of 2002, only false cleavers were seeded. Volunteer canola treatments were omitted due to very poor recruitment during the previous spring. Where subplots were to be cultivated the seed-sand mixture was spread over the east half of the subplot, with tillage proceeding from an east to west direction. This was done to avoid the horizontal movement of seeds beyond the bounds of the subplot as a result of tillage. Where subplots were to remain uncultivated, the seed-sand mixture was spread evenly over the entire subplot area. Immediately after seed-spread, designated subplots were cultivated.

All tillage operations were accomplished using a plot size John Deere sweep cultivator with nine 30cm sweeps (five on first gang, four on second gang) placed on 27cm centers (Enns Brothers Limited, Oak Bluff, MB). Cultivation consisted of one pass to an approximate depth of 5-7cm over each of the allotted subplots. In a given year, cultivation was done in the same direction (east to west) on all subplots. In 2002, to avoid tillage induced movement of seeds beyond the bounds of the subplots cultivation of the plots that were started in the spring of 2001 was done in the opposite direction (west to east) of the initial cultivation. On May 30, 2001 in Petersfield , June 5, 2001 in Komarno, and May 28, 2002 at both sites, wheat (*Triticum aestivum* cv AC Barrie) was seeded in all plots at 103kg/ha using a double disc press drill. Crop seeding was done in the direction perpendicular to that of cultivation.

Spring cleavers seedling emergence counts were taken approximately three weeks post-tillage on June 25, 2001 (spring 2001 plot) and June 27, 2002 (spring 2002 plot). Within each subplot cleavers seedlings were counted in two 50cm by 50cm areas. All identifiable cleavers seedlings were counted, including those in the cotelydon stage.

After counts on June 26, 2001, plots were sprayed with a mixture of 142 g a.i. ha^{-1} fluroxypyr, 99 g a.i. ha^{-1} clopyralid, 554 g a.i. ha^{-1} MCPA ester, 68 g a.i. ha^{-1} clodinafop-propargyl and score adjuvant. Spraying was done using an ATV sprayer equipped with a 3m wide boom and six standard 11001VS TeeJet nozzles at 275 kPa resulting in the application of 54 L ha^{-1} of spray solution. The wheat was allowed to reach maturity and harvested using a Hege plot size combine. Loose straw deposited by the combine was raked from the plots after harvest at both sites.

On September 6, 2001, T1 and T2 subplots were cultivated. Tillage was done in a west to east direction, the opposite of spring cultivation. Two passes with the cultivator were required to penetrate to a depth of 5-7cm. Fall cleavers emergence counts were done approximately four weeks post-tillage on October 8, 2001 using the same methods as described for the spring 2001 emergence counts.

In an attempt to ensure that enough germinable seed was present in the soil seedbank to allow for spring 2002 emergence from plots that were originally seeded in the spring of 2001 (over-wintering experiment), select tillage replicates were augmented with additional cleavers seed in the fall of 2001. Four of the nine tillage replicates were designated to receive seed augmentation at both sites. On October 11, 2001, cleavers seed and sand was spread at 1000 seeds m^2 on the augmented treatment plots. After the seed-sand mixture was spread on the surface, the T1 and T2 plots were cultivated to a depth of 5cm. At the same time, T0 plots were sprayed with glyphosate at 1350 g a.i. ha^{-1} using an ATV sprayer equipped with a 3m wide boom and six standard 11001VS TeeJet nozzles at 275 kPa resulting in the application of 54 L ha^{-1} of spray solution.

3.2.3 Influence of Tillage on Cleavers Seed Position in the Soil Profile

In the fall of 2001, an experiment was started to determine the influence of tillage on the placement of cleavers seed in the soil profile. Because the small, dark colored cleavers seed was extremely difficult to see on the soil surface, highly visible plastic beads were used to simulate actual cleavers seed. The beads were 2mm in diameter and 1.5mm in height, with a small hole in the center. This size of bead was the closest

representation available for cleavers seed which has an average diameter of 1.5mm. The 100 bead weight was approximately 0.93g, which is greater than that of the actual 100 seed weight of cleavers (0.20g). However, no other options were available. Two tillage treatments were considered; tilled and untilled. The tilled treatment consisted of one pass with a sweep cultivator and the untilled treatment was left undisturbed. Due to space limitations it was not possible to replicate tillage treatments for this experiment in any of the four site years. Thus, the plot consisted of two 9.5m by 2.5m areas, one of which was tilled and one remained untilled. Each 9.5m by 2.5m area was further divided into four 2m by 2.5m subplot replicates, each of which received equal amounts of beads. Prior to cultivation 150g of beads were spread by hand onto each 2m by 2.5m subplot.

On the untilled subplots, the beads were spread evenly over the entire area. On the tilled plots beads were placed on the eastern half of the plot with tillage proceeding in an east to west direction; thus, allowing for horizontal movement during cultivation. After beads were spread, tillage was done with a single pass of a plot size John Deere sweep cultivator. Surface counts of beads were done using a $0.0625m^2$ quadrat, which was randomly positioned six times within each 2m by 2.5m subplot. In the spring of 2002, prior to any tillage, surface counts of beads were done again. Also in 2002, soil samples were taken in each subplot as per the procedure outlined for volumetric soil moisture sampling (see Section 3.3). Sampling of bead placement was done at three depths; 0-2cm, 2-4cm and 4-6cm. Three samples at each depth were taken per 2m by 2.5m subplot. These samples were bulked according to depth. Bulked samples were sieved using a 3 ½ / 64 sieve (Can-seed Equipment Winnipeg, MB) to allow for separation of the beads from the remaining material. The number of beads per sample

were counted and recorded. After pre-tillage sampling in the spring of 2002, the 9.5m by 2.5m tilled plot was cultivated in the opposite direction of the previous fall cultivation. Surface bead counts and depth sampling was done again after spring cultivation. This experiment was repeated on new plots in the spring of 2002 with beads being put down in the early spring of 2002 prior to any spring tillage. Both surface counts and depth sampling were done on the new plots as per the methods previously described.

3.3 Characterization of Seedling Recruitment Microsites

After plots were cultivated and the crop seeded, soil bulk density measures were taken using 5cm diameter tins. In the spring of 2001, measurements were taken from a subplot within six and nine tillage replicates at Komarno and Petersfield, respectively. Three tins per subplot were filled by placing the tins open side down on the soil surface and applying even pressure until they were sunk 3.5cm into the soil. Tins were then removed such that the soil remained within the tin. Soil from each tin was weighed and dried at 105 °C for 48 hours. Bulk density was then calculated using the soil dry weights and individual tin volume.

Hourly soil temperature was measured using StowAway Tidbit devises. In 2001, tidbits were placed within one randomly selected subplot in six replicates of T0, T1 and T2 treatments at each site. The tidbits were buried such that the measurement end remained 4cm below the soil surface. In 2002, tidbits were placed in both plots initiated in 2001 (over-wintering experiment) and those started in 2002 (spring 2002 experiment). In the over-wintering experiment, tidbits were placed in a single randomly selected subplot within two replicates of T0, T1 and T2 tillage treatments at each site. In the

spring 2002 experiment, tidbits were placed in a randomly selected subplot within three replicates of T0 and T2 tillage treatments at each site. In 2002 only, at each site two tidbits were placed within each selected subplot, allowing for measurement at two depths; 4cm and 1cm below the soil surface. Tidbits placed near the soil surface were stabilized using plastic stakes.

At each site in 2001 and 2002, a tipping bucket rain gauge with HOBO event logger and HOBO Pro Temp/External Temp (Onset Computer Corporation Bourne, MA), were used to measure precipitation and air temperature, respectively. The HOBO was attached to a wooden stake which was driven into the ground until the main body of the devise remained approximately 1m above the ground and the measurement probe approximately 20cm above the soil surface. Both the main body of the devise and the measurement probe were covered with white plastic containers to avoid measurement errors associated with the impact of direct solar radiation. HOBOs were programmed to record hourly air temperature measurements. Tipping buckets were fastened to a wooden base and placed on the soil surface. The base was leveled to ensure proper function. Air temperature and precipitation were recorded at both Komarno and Petersfield in the spring of 2001 and 2002. In the fall of 2001, the devises failed to record temperature and precipitation data. Thus, data was obtained from weather stations located within close proximity to the two experimental sites. This consisted of data from a Teulon weather station (SW23-16-2E) which represents an approximation of the conditions at Komarno and data from a Petersfield weather station (SW1-16-3E) located directly south of the Petersfield plot (Agrometeorological Centre of Excellence, Carmen, MB).

Gravimetric soil moisture samples were taken at both sites in both years. Samples were taken approximately every two days after tillage treatments were applied. In the spring and fall of 2001, samples were taken from a randomly selected subplot within six replicates of T0, T1 and T2 treatments in Komarno and nine replicates of T0, T1 and T2 in Petersfield. All samples were taken from between the crop rows. In the spring of 2002, sampling took place in a randomly selected subplot within three replicates of the T0, T1 and T2 treatments in the over-wintering experiment and three T0 and T2 replicates in the spring 2002 experiment. This was accomplished with the use of a 2cm wide Dutch auger (Canadian Forestry Equipment Ltd., Edmonton, AB). Three sub-samples were taken per subplot to a depth of 5cm. The three samples were bulked and a final sample was taken after mixing. These samples were stored in a tin with a tightly fitting lid to minimize any moisture loss prior to weighing. Samples were weighed the day of sampling and then dried in an oven at 105 °C for 48 hours. Dried samples were weighed and recorded. Gravimetric soil moisture was calculated using the following equation:

$$\frac{\text{Mass of Wet Soil} - \text{Mass of Dry Soil}}{\text{Mass of Dry Soil}}$$

In 2002, in addition to gravimetric soil moisture samples, volumetric soil moisture samples were taken approximately every two days after tillage treatments were applied. Samples were taken from a randomly selected subplot from within two T0, T1 and T2 replicates in the over-wintering experiment and three T0 and T2 replicates in the spring 2002 experiment. All samples were taken from between the crop rows. Sampling was done with the use of a 5cm diameter by 2cm depth copper ring with one beveled cutting

edge. Prior to sampling, a vertical plane of soil was exposed by removing a wedge of soil. The sampling ring was then placed on the surface near to the exposed plane. The ring was pushed into the soil profile using constant pressure. A broad flat knife was used to cut into the soil plane immediately below the ring, allowing it to be removed while keeping the soil sample intact. The soil was removed from within the ring using a flat spatula. The sample was placed directly into a heat resistant plastic container with a tightly fitting lid. Samples were taken at 0-2cm, 2-4cm and 4-6cm depths, with each subsequent sample taken directly below the previous sample. Samples were weighed and dried at 95 °C for 48 hours. Dry weights were obtained and samples were discarded. Volumetric soil moisture was calculated by multiplying the gravimetric soil moisture by the dry soil bulk density.

3.4 Statistical Analysis

SAS 8.02 statistical software was used for all analyses. Prior to analysis, all data were checked for normality using the Shapiro-Wilk test. Normal probability plots and (Residual * Fitted) plots were also used to indicate normality or non-normality of the data. In our experiment, all data met the requirement of normality, so no data was transformed prior to analysis.

Though the experiment was designed as a split plot with the mainplots blocked, no analysis was done investigating differences between seeding treatments. Thus, only the differences between the mainplot treatments (tillage treatments) were of interest. As a result, the data was analyzed as a randomized complete block design (RCBD) or a

completely randomized design (CRD), depending on the sampling scheme. Analysis of variance procedures (PROC GLM) were used.

For the spring 2001 and fall 2001 experiments at Komarno, false cleaver emergence counts were analysed as a RCBD and soil temperature, soil gravimetric moisture, soil bulk density data were analyzed using a CRD. Analysis based on a CRD was used when sampling of all tillage treatments was not done within a single block. For the spring 2001 and fall 2001 experiment at Petersfield, soil temperature data was analyzed using a CRD, all other measurements were analyzed using a RCBD. For the spring 2002 experiments, all measurements at both sites were analyzed using a RCBD. For the over-wintering plots all measurements at both sites were analyzed using a RCBD except for the emergence counts which were separated into augmented and non-augmented replicates and analyzed using a CRD. Mean separation was accomplished with the Fishers Protected LSD test. Means were considered significantly different if p-values were less than 0.05. In cases where there was a significant difference between sites and/or years, the data for year and/or site was analyzed separately, otherwise the data was pooled.

Data which was collected by sampling repeatedly over time (soil moisture, soil temperature) was analyzed to identify any (Date * Treatment) interactions. In those situations where interactions were present, this data was re-analyzed using repeated measures analysis. This procedure analyses data within each individual day, and thus, accounts for the inability to randomize time. From this, one can identify the days during which significant treatment effects and/or interactions took place.

Where multiple depths were sampled (soil temperature, soil volumetric moisture) the resulting data was analyzed to identify any (Depth * Treatment) interactions. Where interactions occur, data is re-analyzed to investigate significant depth effects for each separate treatment.

For the experiment investigating the impact of tillage on cleavers seed placement (3.2.3), no statistical analysis was possible due to the absence of tillage treatment replication. As a result only the means and standard errors were calculated for this experiment.

CHAPTER 4

Results and Discussion

4.1 Cleaver Seed Collection and Characterization

4.1.1 Species Identification

DNA analysis using flow cytometry first expanded from solely medical use to use in the plant sciences in the late 1980's (Dolezel 1991). Since that time this technique has become routine in many laboratories. The use of flow cytometry for characterizing ploidy levels proved to be an effective method of species identification in cleavers. The mean amount of DNA present in plant cells of the different specimens are listed in Table 1 (Appendix B). Measurements on the known specimens expressed an approximate 3:1 ratio in DNA content of *G. aparine* species relative to *G. spurium*, suggesting that *G.aparine* is a hexaploid and *G. spurium* a diploid. Other researchers have shown similar relationships between the chromosome number in the two species (Malik and Vanden Born 1988; Kliphuis 1980; Moore 1975). When the peak values of the unknown samples were compared to those of the known specimens it was clear that all nine plants most closely resembled the sample of *G. spurium* obtained from Herbiseed.

Using the root squash technique, the 2N chromosome number was determined for the five plant samples grown from the Brett Young Seeds Ltd. seedlot. All plants tested had a 2N chromosome number of twenty. This result identifies all five plants as being *G. spurium*.

Based on the combined results of flow cytometry and root squash procedures, we suggest that the Brett Young Seeds Ltd. seedlot was comprised primarily, if not entirely, of *G. spurium*. Scientists have often suspected that the predominant cleavers species present in agricultural fields on the Canadian prairies was *G. spurium* rather than *G. aparine*. The results of this experiment support these suspicions. However, due to the large seed population being considered in this study, testing of additional samples would be necessary to conclusively characterize the seedlot in terms of the species composition.

4.1.2 Seedlot Germination

The results of the two runs of the germination test were not significantly different, as a result they were combined. Based on a total of thirty replicates, the percent germination (standard error) for our seedlot was 62 (±2.2)%. When seeds were planted in a soil medium, it appeared as though emergence occurred at a greater rate and germination levels were higher than when seeds were germinated on petri plates. Based on this observation, it is possible that emergence may be enhanced in soil versus petri plates. Thus, the percent germination occurring in the field may be greater than that estimated using the petri plate method.

4.1.3 Impact of Simulated Seasonal Transition on Seed Germination

4.1.3(i) Temperature Effects

The trend in the germination response was similar for all three runs of this experiment (Appendix C). However, due to differences in the extent of the germination response, the three runs were analyzed separately. In run 1, the temperature

measurements taken from within the boxes indicated that the actual average day and night temperatures were 14.6°C and 15.3°C for the low temperature treatments, and 16.6°C and 20.3°C for the high temperature treatments. Thus, the actual temperatures of the low temperature treatment were slightly elevated and the actual temperatures in the high temperature treatments were slightly reduced. Based on the germination counts for run 1, average germination in the 10-15°C treatment was 14% greater than that occurring in the 17-22°C treatment, for the plates moistened with a 0.1% solution of KNO_3. When distilled water was used for the plates, the difference in germination between the cool and the warm cabinets was more pronounced. In run 1(distilled water), the germination in the 10-15°C treatment was 38% greater than that occurring in the 17-22°C treatment. Though the difference in germination between temperature treatments was greater when distilled water was used, the overall number of germinated seeds was reduced in the plates moistened with distilled water compared to KNO_3.

In an attempt to reduce the possibility of temperature overlap occurring between the cool and the warm treatments, slightly different temperature treatments were investigated for the second and third run of this experiment. The low and high temperature treatments applied in runs 2 and 3 were; 8-15°C and 17-24°C, respectively. The actual average day and night temperatures for run 2 and 3 were 10.2°C and 12.8°C (run 2) for the low temperature treatment and 18.1°C and 22.9°C (run 2) for the high temperature treatment, and 8.9°C and 9.4°C (run 3) for the low temperature treatments and 17.5°C and 22.7°C (run 3) for the high temperature treatments. The actual temperatures of the high temperature treatments were quite close to the intended range. For the low temperature treatments, the actual temperatures were somewhat elevated, and

the temperature change from day to night was reduced compared to the target. Germination in the plates wetted with KNO_3 was 30% and 14% greater in the 8-15°C cabinet compared to the 17-24°C cabinet for run 2 and 3, respectively. When considering the plates wetted with distilled water, the germination was 66% and 71% greater at the 8-15°C temperature when compared to 17-24°C for runs 2 and 3, respectively. When all three runs of this experiment are considered, germination of false cleavers was consistently greater in the low temperature treatments relative to the high temperature treatments. The obvious differences in percent germination between low and high temperature treatments may provide an indication of the form of growth habit that the false cleavers population being investigated possessed. Masuda and Washitani (1992) have shown that the emergence timing of false cleavers can vary. They observed differences in the germination phenologies of two ecotypes of *Galium spuirium* var. *echinospermon.* One ecotype responded as a summer annual, exhibiting the release of primary dormancy by moist chilling (4°C). The second ecotype behaved as a winter annual, where primary dormancy was released after moist warming (25°C). Secondary dormancy was induced in the spring germinating and autumn germinating ecotype by rising and falling temperatures, respectively (Masuda and Washitani 1992). The result of our experiment show that germination of false cleavers will occur more readily when dry seeds are exposed to a warm pretreatment followed by cool conditions post-imbibition. This behavior would typically correspond to a winter annual growth habit, because germination appears to be responding to a warming period. However, this experiment was not designed as a factorial, and thus, we could not determine the relative importance of the pretreatment conditions and the post-imbibition conditions for seed

germination. It is well known that the environmental conditions that seeds are exposed to after imbibition will affect their ability to germinate, but the environmental conditions that dry seeds are exposed to may also affect their post imbibition germination level. The relationship of dry storage conditions to post-imbibition germination levels is species specific. Germination of virginia pepperweed (*Lepidium virginicum* L.) and orchard grass (*Dactylis glomerata* L.) was shown to increase after dry storage at -18°C and -75°C, respectively, where as, no germination of ironweed (*Veronica anthelmintica* L.) occurred after 24 weeks of storage at 0.6°C and subsequent placement under conditions favorable for germination (Baskin and Baskin 1998c). In addition to being species specific, the germination response may vary with the duration of dry storage. *Veronica anthelmintica* germination increased after 96 weeks of storage at 0.6°C compared to germination after 24 weeks (Baskin and Baskin 1998c). In our experiment, if we assume that the dry seed pretreatment was influencing the state of the false cleavers seed dormancy, the germination response observed at low temperature post-imbibition suggests that seed dormancy increased during the cold pretreatment and decreased during the warm pretreatment. This behavior would be consistent with an autumn germinating species. However, if we assume that the dry seed pretreatment did not have a significant effect on the dormancy of false cleavers seed, then the decrease in dormancy at low temperatures and increasing dormancy at high temperatures would suggest that the false cleavers seedlot used in this experiment conforms to the behavior of a species expressing a traditional summer annual growth habit. Comparing the indoor study results to observations made of false cleavers recruitment in the field suggests that the second scenario may be more indicative of this population (Table 4-1). False cleavers

emergence levels observed in the field in the spring of 2001/2002 were considerably higher than those observed in the fall of 2001. Considering that approximately 1000 seeds m^{-2} were applied to each experiment, and the average recruitment in the spring of 2001 for the tilled and untilled treatments was 458 and 168 seedlings m^{-2}, respectively, it is unlikely that the lower recruitment in the fall of 2001 was associated with a seed limitation. Rather, it appears as though the false cleavers seedlot used in this study is behaving as a summer annual weed.

4.1.3(ii) The Influence of Nitrates on Germination

The results of the false cleavers germination experiment also indicate that the germination of false cleavers is sensitive to the presence or absence of nitrates, in that, without nitrates germination was reduced (Appendix C). This relationship appears to be enhanced under moderately high temperature conditions (17-24°C). Other researchers have identified nitrates as being influential in cleavers germination (Van der Weide 1993; Malik and Vanden Born 1987c; Froud-Williams 1985; Sjostedt 1959). When seeds were incubated at 21°C, those imbibed with a nitrate solution approached 100% germination after 10 days, where as, those imbibed with distilled water reached only 76% germination during the same period (Malik and Vanden Born 1987c). Sjostedt (1959) found that after 21 days of incubation, cleavers germination in plates wetted with H_2O, KNO_3 and soil filtrate was 4, 23 and 32%, respectively.

The amount of nitrogen applied in this experiment was large relative to what is likely present in agricultural soils. In our experiment a 0.1% solution of KNO_3 was used. This is equivalent to 150 ppm N in water. This is high compared to the average nitrogen

application rate used on agricultural fields. In Manitoba, the most common nitrogen rates applied for spring wheat, barley and oat crops range from 70 kg N ha^{-1} to 90 kg N ha^{-1} (Thomas et al. 1997). The actual applied rate will vary among fields depending on soil moisture conditions, the crop species to be seeded, the target yield and the amount of residual nitrogen present in the soil. Assuming an average application rate of 80 kg N ha^{-1}, which is equivalent to 36 ppm N in soil, the amount of nitrogen applied in our experiment was approximately four times the amount of the average nitrogen application on agricultural fields in Manitoba. Also, the availability of the nitrogen to the seeds may be enhanced in water relative to soil, where nitrogen can become adsorbed to soil particles and utilized by soil microbes. The actual nitrogen requirement for enhancing false cleavers germination is not known. Though levels used in this experiment were higher than expected in a field, the lower levels in the field still may be sufficient to enhance germination.

It is difficult to estimate the amount of nitrogen present at each of the field sites considered in this experiment. In the 2000 season, Petersfield and Komarno were seeded to barley and canola, respectively. Data recorded in Manitoba from 1990 to 1998, showed that residual soil nitrogen (0-24cm) in the spring following barley or canola averaged 48 (21.8 ppm) and 43 (19.5 ppm) kg ha^{-1}, respectively (Unpublished data obtained by AGVISE Laboratories, reported on Manitoba Agriculture and Food website). In Komarno, there was additional fertilizer added in the spring of 2001, thus, at this site residual nitrogen levels would likely have been even greater than estimates. Nitrogen levels within the soil will vary depending on the soil type, weather conditions

(temperature and moisture), landscape position (high versus low) and management practices (fertilization, crop sequence, residue management).

Regardless of the average level of nitrogen estimated for a site, the actual nitrogen levels will vary spatially. Pockets of high and low soil nitrogen levels will likely occur in most fields. These regions of variable soil nitrogen can be viewed at a coarse scale (topographic highs and lows within a field) or at a very fine scale (areas of microbial nitrogen depletion or deposition within a soil clod). Levels tend to be greatest near the surface and reduced at depth. Estimated total nitrogen for the gleyed rego black chernozemic soil at Komarno is 0.88, 0.21 and 0.09 % when measured from 0-5, 5-10 and 10-16cm, respectively (Pratt et al. 1961). At Petersfield, estimated total nitrogen for the gleyed dark grey chernozemic soil would then be 0.17, 0.11 and 0.03 % when measured from 0-5, 5-10 and 10-36cm, respectively (Pratt et al. 1961). Thus, the region of the greatest seedling recruitment (0-4cm) (du Croix Sissons et al. 2000) coincides with the region of greatest soil nitrogen. Verhagen et al. (1995) investigated the horizontal variability of soil nitrogen and found that within a six hectare area the total nitrogen in the early part of the growing season varied between 21 and 53Kg ha^{-1}. Where areas of very low soil nitrogen occur, the ability of false cleavers seed to germinate may be reduced.

4.2 Cleavers Seedling Recruitment as Influenced by Tillage

4.2.1 Site Description

The following descriptions are based on two sites; Komarno and Petersfield. At each of these sites a single experiment was established in the spring of 2001 and another

in the spring of 2002. Measurements made on these experiments in the spring following their establishment capture the short term recruitment dynamic occurring immediately after false cleavers seed spread in a given spring. In addition to the short term dynamic, we were interested in observing the changes in recruitment that occurred over a longer time period. In order to capture this longer term dynamic, the experiments which had been established in the spring of 2001 were observed over approximately two seasons, starting in June of 2001 and ending in July of 2002. During this period, the recruitment dynamic for three separate periods was observed on the experiments established in the spring of 2001. False cleaver recruitment in the spring of 2001 was recorded. In addition, false cleaver recruitment in the fall of 2001 and the spring of 2002 was also recorded. Measurement in the spring of 2002 was intended to capture the impact of a single winter season on false cleavers recruitment. In an attempt to avoid confusion, the experiments that were established in the spring of 2001, but were observed in the spring period in 2002, will be referred to as the over-wintering experiments. Thus, at Komarno and Petersfield, the spring 2001, fall 2001 and over-wintering experiment is the same plot with measurements made at different time periods. This experiment is different from the spring 2002 experiment, which was newly established in 2002.

In the fall of 2001, we added additional false cleavers seed to some of the over-wintering plots. The four tillage replicates which were seeded with additional false cleavers seed in the fall of 2001 are referred to as the augmented treatments in the over-wintering experiment. In addition to receiving supplementary seed, the T1 and T2 tillage treatments in the augmented replicates were tilled a second time in the fall of 2001 after the false cleavers seed was spread. The remaining five tillage replicates in the over-

wintering experiments did not receive any additional false cleavers seed or any additional tillage in the fall of 2001. These replicates are referred to as the non-augmented treatment in the over-wintering experiment.

4.2.1(i) Surface Residue Levels

Based on a visual assessment prior to the start of the experiments, the residue cover in the spring of 2001 was estimated to be between 5-10% at Petersfield. At Komarno, there was no residue present on the soil surface in the spring of 2001. Surface residue cover in the spring 2002 experiments was near zero at both sites. As a result, residue cover was not expected to impact recruitment in the spring 2001 or spring 2002 experiments. No residue measures were recorded in the fall of 2001 experiment.

In the spring of 2002, residue measures were also recorded for the over-wintering experiments at Komarno and Petersfield. Because this experiment had been seeded to wheat in the spring of 2001, the amount of stubble present on the surface was much greater than that present in the spring 2001 or spring 2002 experiments. In the over-wintering experiment at Komarno and Petersfield, the residue cover measured in the spring of 2002 was not different between the augmented and non-augmented treatments. As a result, residue cover measures for the augmented and non-augmented treatments were combined. At Komarno, the surface cover in the over-wintering experiment was estimated at 90.0%, 43.0% and 41.5% for the T0, T1 and T2 tillage treatments, respectively. At Petersfield, the surface residue cover in the over-wintering experiment was estimated at 63.5%, 30.5% and 27.0% for the T0, T1 and T2 tillage treatments, respectively. Surface residue cover was greater in the untilled treatments relative to the

tilled treatments. Increased residue cover may impact weed seedling recruitment by increasing seed burial, which is necessary for the recruitment of light sensitive species such as false cleavers. However, in our experiment the differences in surface residue cover between tillage treatments did not translate into significant recruitment differences. Though not statistically significant, there was a trend towards greater recruitment in the untilled (T0) treatments relative to the tilled treatments (T2) in the augmented and non-augmented treatments in the over-wintering experiment at Petersfield, and the non-augmented treatments in the over-wintering experiment at Komarno (Table 4-1). This result is similar to that obtained by Boyd (2003), who did not find significant differences in cleavers recruitment when surface residue cover was maintained at 0%, 20% and 90%, yet he did observe a general trend towards greater emergence at higher residue cover levels (Boyd 2003).

4.2.1(ii) Spring Air Temperature

Measurement of air temperature is important when studying seedling recruitment, because soil temperature is related to air temperature. Reimer and Shaykewich (1980) showed a strong correlation for the mean monthly air temperature and the mean monthly soil temperature at 1cm measured in June, July and August. Soil temperature can have a significant effect on seedling recruitment. All plant species have a maximum and minimum temperature requirement above and below which the rate of germination is slowed or stopped (Oryokot et al., 1997a). Mean air temperatures and long term averages for these sites are presented in Appendix D. In the spring of 2001, the average daily air temperature from June 7, 2001 (Julian day 158) to July 5, 2001 (186) was 18.0°C for both

Komarno and Petersfield. The mean daily maximum and daily minimum temperatures averaged over both sites during the same period were 23.8°C and 10.0°C, respectively. In 2002, the average daily temperature from June 2, 2002 (153) to June 30, 2002 (181) was 18.2°C for both Petersfield and Komarno. The average daily maximum and minimum temperatures during the same period in 2002 were 24.8°C and 11.4°C, respectively. The mean temperature values were nearly identical for 2001 and 2002. These values are also similar to the climate averages for Selkirk, MB, which represents the closest Environment Canada weather station to both experimental sites. Based on data accumulated from 1971-2000 (no more than five years missing), the daily mean temperature for June is 17.3°C with the mean daily maximum and daily minimum temperatures being 22.9°C and 11.6°C (Environment Canada). Thus, at both Petersfield and Komarno the daily maximum temperatures were only slightly above average and daily minimum temperatures were only slightly below average. Overall, the air temperature measured in 2001 and 2002 falls within the normal temperature range.

4.2.1(iii) Fall Air Temperature

Fall air temperatures recorded from Sept. 6, 2001 to Oct. 8, 2002 resulted in a mean temperature of 10.6 °C for both Komarno (Teulon Weather Station) and Petersfield (Petersfield Weather Station). The average daily maximums and daily minimums over the fall period were 17.7°C and 3.9°C, respectively, for the Komarno (Teulon Weather Station) and Petersfield (Petersfield Weather Station) sites combined. Based on 29 year averages, the mean temperature for the month of September measured at Selkirk, MB is 12.4°C. Thus, the mean temperature for the two sites was lower than average in the fall of 2001 relative to average fall temperatures. The daily maximum and daily minimum

Table 4-1. Mean false cleavers seedling emergence (plants m^{-2}) at two sites, Petersfield and Komarno MB, measured in the spring 2001experiment (measurement in spring 2001), spring 2002 experiment (measurement in spring 2002), fall 2001 experiment (measurement in fall 2001) and over-wintering experiment (measurement in spring 2002), as affected by two or three tillage treatments; no additional tillage after the start of the experiment (T0), a single tillage operation in the fall only (T1), and one spring and one fall tillage operation (T2 [a]).

	Petersfield				Komarno				Pooled[b]
	Fall	Spring	Over-wintering		Fall	Spring	Over-wintering		Spring
Factor	2001	2002	Augmt [c]	Non-augmt [c]	2001	2002	Augmt [c]	Non-augmt [c]	2001
Tillage T0	2a [d]	130a	116a	36a	5a	277a	95a	14a	167a
T1	4a	-	66a	30a	24b	-	85a	16a	-
T2	3a	277b	80a	17a	16b	376a	102a	5a	458b
LSD	2.8	56.4	61.9	24.8	7.9	138.4	42.8	13.6	73.7

[a] For the spring 2001 and spring 2002 experiments, the T2 treatment would include a single tillage operation in the given spring. For the fall 2001 experiments, T2 would include one spring 2001 tillage operation and one fall 2001 tillage operation. For the over-wintering experiments, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.

[b] Emergence counts in the spring 2001 experiments were not significantly different between sites therefore data was pooled for between sites.

[c] Over-wintering experiments were divided into augmented (Augmt) or non-augmented (Non-augmt) treatments based on if they had or had not received additional false cleavers seed (1000 seeds m^{-2}) in the fall of 2001.

[d] Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

temperature based on long term records is 18°C and 6.8°C, respectively. The average daily minimum temperatures experienced at both sites were lower than average. Whether the uncommonly low mean temperature occurring in the fall of 2001 led to the reduced recruitment we observed during that period is unclear. In our indoor experiments, germination was possible at average temperatures as low as 8.9°C. Malik and Vanden Born (1987b) identified 10-20°C (night-day temperatures) as favorable for false cleavers germination. An average daily minimum temperature of 3.9 may have limited recruitment.

4.2.1(iv) Spring Precipitation

The timing and intensity of rainfall events that took place in the spring at Komarno and Petersfield are depicted in Figure 4-1 for 2001 and Figure 4-2 for 2002.

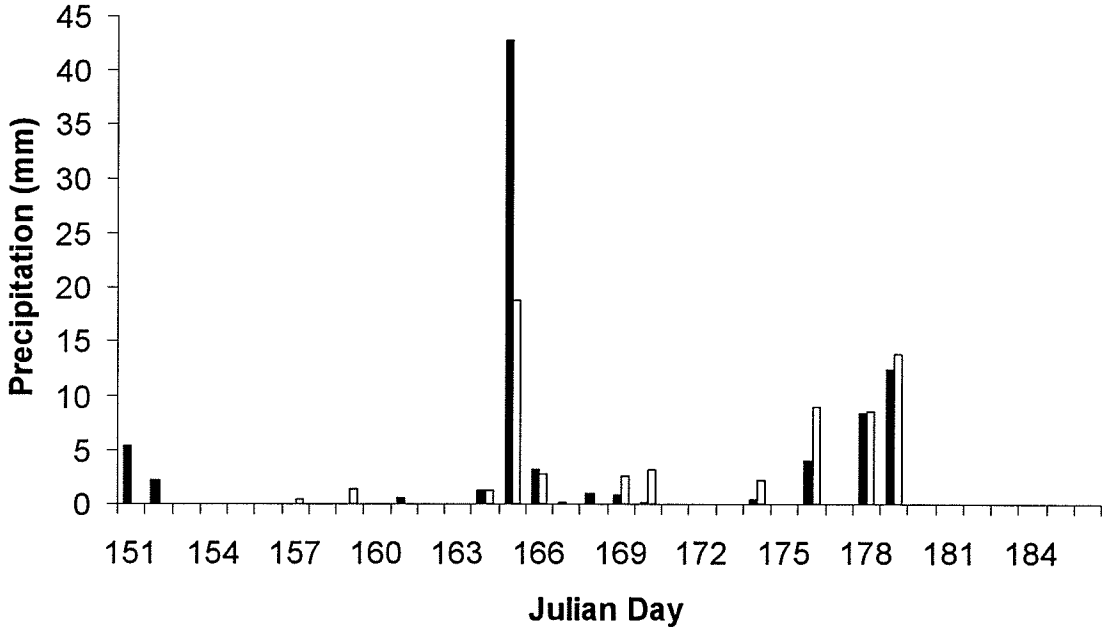

Figure 4-1. Daily accumulated precipitation in the spring of 2001 at Petersfield (■) and Komarno (□), MB. Julian day 151 is May 31.

The accumulated precipitation from June 1, 2001 (Julian day 151) to June 26, 2001 (176) was 41.6mm and 62.0mm for Komarno and Petersfield, respectively (Figure 4-1). In 2002, the accumulated precipitation from June 1, 2002 to June 26, 2002 was 86.2mm and 73.8mm for Komarno and Petersfield, respectively. According to the 29 year climate normals for Selkirk, MB, the average precipitation for the month of June is 93.0mm (Appendix C). This value is based on data obtained within the years 1971-2000, with a minimum of

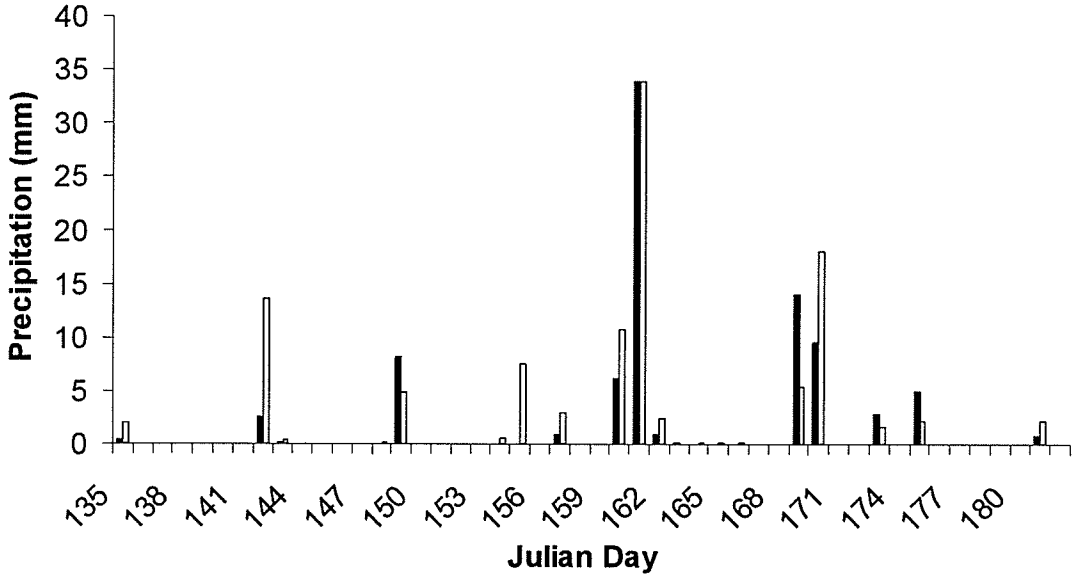

Figure 4-2. Daily accumulated precipitation in the spring of 2002 at Petersfield (■) and Komarno (□), MB. Julian day 135 May 15.

fifteen sample years contributing to the average value (Environment Canada). Therefore, the values recorded during the 2001 and 2002 spring sampling periods at both Komarno and Petersfield were lower than average. In 2001, the most extreme rainfall event took place on June 14, 2001(165) at both sites. Maximum recorded precipitation was 42.8mm and 18.8mm for Petersfield and Komarno, respectively. In 2002, the most extreme rainfall event took place on June 10, 2002 (161) at both sites. Maximum recorded

precipitation was 34.0mm for both Komarno and Petersfield. In both 2001 and 2002, extreme rainfall events resulted in the accumulation of water on the soil surface at Petersfield. For experiments initiated in 2001, the surface ponding was focused in the southern section of block four and the northern portion of block 3. For experiments initiated in 2002, ponding did occur, but was less pronounced. The presence of standing water may have affected the recruitment and survival of false cleavers. Ponding did not occur at Komarno, do to the higher infiltration rate of the silt loam soil at this site.

4.2.1(v) Fall Precipitation

Water is one of the key requirements for seed germination. False cleavers germination is reduced at moisture retention levels below -2.5 bars and prevented at levels below -7.5 bars (Malik and Vanden Born 1988). The accumulated precipitation for the fall of 2001 (Sept. 6 – Oct.8) was 19.6mm and 17.6mm for Komarno (Teulon Weather Station) and Petersfield (Petersfield Weather Station), respectively (Appendix C). The 29 year average precipitation for September, based on the Selkirk Weather Station data, was 53.8mm. The values recorded at Petersfield and Komarno were much lower than average. The maximum rainfall accumulated in a single event took place on Sept. 22, 2001 at both sites. During this event 12.4mm and 11.4mm of precipitation was deposited at Komarno (Teulon Weather Station) and Petersfield (Petersfield Weather Station), respectively. Thus, in the fall of 2001, 63% (Komarno) and 65% (Petersfield) of the total precipitation accumulated between Sept. 6, 2001 and Oct.8, 2001 occurred during a single rainfall event. Both sites were extremely dry for the majority of the fall period in 2001. Dry conditions may have limited false cleavers recruitment.

4.2.2 Tillage Intensity and Cleavers Recruitment

4.2.2(i) Background Cleavers Population

Though seedbank sampling has typically been done to characterize weed communities, and predict future infestations, more recently the utility of this technique has been questioned. Studies have shown that the weed community characterization using seedbank sampling techniques does not provide an accurate representation of the weed community (Derksen and Watson 1998; Chancellor et al. 1983). Seedbank sampling typically requires that soil core samples are grown out under greenhouse conditions. This can lead to errors, as certain weed species are more or less apt to recruit under greenhouse conditions. For example, Derksen and Watson (1998) found that green foxtail (*Setaria viridis*) recruited well in the greenhouse whereas wild oat (*Avena fatua*) did not. This means that seedbank analysis may result in the over representation of some weed species (green foxtail) and the under representation of others (wild oat). Further difficulties may arise when determining the frequency of sampling, the sample size and the timing of sampling that will result in more representative data. Overall, the data resulting from seedbank sampling must be interpreted knowing the shortcomings of this technique.

The results of seedbank sampling done in our experiment in 2001 indicate that the background population of cleavers was low at both Komarno and Petersfield. No cleavers seedlings emerged from any of the soil samples taken from the Komarno site. Though the results of seedbank sampling would suggest that cleaver populations were essentially absent from Komarno, observations of cleaver recruitment in the area surrounding our experiments suggests that cleavers were present at the site prior to the

start of the experiment. This was confirmed through communication with the land owner who observed cleavers on the site in previous seasons. Population densities at Komarno were low, and the majority of the infestation appeared to be located directly adjacent to a treed shelter belt. For Petersfield, of the 108 plots sampled, a total of only five cleavers seedlings emerged during both the initial and post-vernilization counting periods. However, field observations at Petersfield suggest that cleavers populations were present prior to the start of the experiment. Again, population densities were low and the infestation appeared to be focused near a treed area at the field margin. The occurrence of cleavers near field margins may not be a coincidence. The conditions in margin habitats may be more favorable to cleavers recruitment than in the field itself. Moisture and temperature conditions may be different in the margin relative to the field. At Komarno and Petersfield, the presence of tall trees provided shade to much of the margin area which may have led to conditions of increased moisture and reduced temperature compared to field conditions. Field margins would have provided an environment that was free of weed control pressure. Because producers don't often actively control weeds in field margins, well suited and competitive weeds can thrive in these areas. Successful seed production and shed acts to build up the weed seedbank in field margins. Thus, the potential combination of highly suitable environmental conditions, less control pressure and a sizable seed store in the soil provides an opportunity for successful false cleavers establishment and continued recruitment in field margins.

Emergence counts done within the control plots, which did not receive any supplemental cleavers seed, confirm that background populations were low. Counts done in the spring 2001 experiments recorded no emergence at Komarno and an average of

only 1 plant m^{-2} in control subplots at Petersfield. In the fall 2001 experiments, average cleavers emergence in the control subplots was 2 plants m^{-2} at both sites. In the spring 2002 experiments, emergence in the control subplots was 0 plants m^{-2} at Komarno and 2 plants m^{-2} at Petersfield. Emergence in the control subplots was greater in the over-wintering experiments. At Petersfield the emergence in the control subplots averaged 11 plants m^{-2} and 7 plants m^{-2} for the augmented and non-augmented treatments in the over-wintering experiments, respectively. Emergence in the control subplots at Komarno averaged 1 plants m^{-2} and 2 plants m^{-2} for the augmented and non-augmented treatments in the over-wintering experiment, respectively. The slight increase in false cleavers emergence in the control subplots within the over-wintering experiments may have been associated with seed movement, by tillage or natural forces, from the treatment subplots that were seeded with false cleavers into the control subplots. The over-wintering experiments were exposed to more vehicle traffic than the spring 2001 or spring 2002 experiment, as a result of additional tillage and seeding operations,. As well, the over-winter experiments were exposed to a winter period, where freeze-thaw forces may have resulted in between-subplot seed movement. Thus, there was a greater propensity for subplot to subplot seed movement in the over-wintering experiments relative to those experiments that were initiated in the spring.

4.2.2(ii) False Cleavers Recruitment in the Spring

Spring false cleavers emergence counts were done on June 25, 2001 and June 27, 2002. The results of the counts done for the spring 2001 and spring 2002 experiments are shown in Figure 4-3.

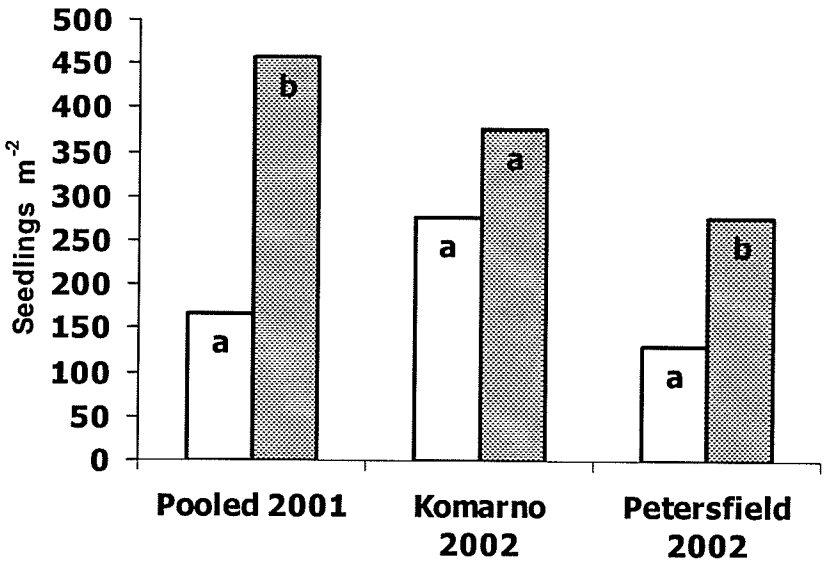

Figure 4-3. Spring false cleavers recruitment over four site years for tilled (▨) and untilled (□) treatments. Within each site year, columns with the same letter are not significantly different as determined by the Fishers Protected LSD means separation test (α= 0.05).

False cleavers recruitment in the tilled treatment was significantly greater than recruitment in the untilled treatment in three of four site years. In 2001, the level of emergence observed at Petersfield and Komarno was not significantly different, therefore, the data was pooled between sites. Emergence recorded in the untilled experiments tended to be focused largely within the crop row, suggesting that recruitment may have been stimulated by burial associated with crop seeding. In 2002 at Komarno, the difference in cleavers emergence between the tillage treatments was not significant (Figure 4-3). However, the trend towards greater recruitment levels in the tilled treatments was consistent (Table 4-1). During the crop seeding operation in the spring of 2002, soil conditions were dry in comparison to the spring 2001 seeding conditions. This may have led to an increase in the proportion of false cleavers seed buried during seeding in the untilled. The absence of a significant tillage treatment effect at Komarno in the

spring of 2002 may have been attributed to enhanced false cleavers seed burial during crop seeding.

Relative to recruitment levels recorded in the spring of 2001, emergence in the spring of 2002 was slightly reduced over all treatments except for the untilled treatment at Komarno (Table 4-1). The general reduction in false cleaver recruitment in 2002 versus 2001 emphasizes the year to year variation that can occur in weed seedling recruitment. The specific reasons for the differences that occurred between years are difficult to identify. At both sites, mean air temperature did not appear to vary greatly between the spring of 2001 and 2002 (Appendix D). Accumulated precipitation for the spring period was similar in Petersfield for both years, but approximately 25mm greater in 2002 then in 2001, at Komarno (Appendix D). Increased precipitation may have influenced recruitment levels at Komarno, specifically in the untilled treatments. More rainfall may have increased the proportion of surface placed seeds that were buried by soil particles or moved into soil openings by raindrop action. It is unlikely that increased precipitation affected recruitment directly by increasing soil moisture levels, as the measured soil gravimetric moisture did not vary between the spring of 2001 and 2002 at Komarno (Table 4-2). However, this measure represented a composite of soil collected from 0-6cm, so it does not clearly capture the variation in time in soil moisture taking place nearer the soil surface. Between site variation in emergence was also evident from the recruitment levels recorded in the spring of 2002, but not in 2001. At Komarno in 2002, false cleavers recruitment was significantly greater than at Petersfield. Differences in the proportion of emergence between the two sites may be associated with the recorded differences in precipitation between sites. Differences in soil type between the sites may

have also led to site to site variation in recruitment. The physical properties of the silt loam at Komarno and the clay at Petersfield would likely differ, as would water holding capacity (De Jong 1982), nutrient availability, soil structure, soil pH (Pratt et al. 1961) and thermal characteristics.

4.2.2(iii) False Cleavers Recruitment in the Fall

False cleavers emergence in the fall 2001 experiments was very low (Table 4-1). Based on the October 8, 2001 emergence counts, there was no significant tillage effect on false cleavers recruitment at Petersfield. The average fall emergence recorded for the three tillage treatments was only 3.0 (±0.55) plants m^{-2}. At Komarno, false cleavers emergence in the fall was not significantly different between the two tilled treatments (T1 and T2). Average emergence for the tilled treatments was 20.0 (±2.59) plants m^{-2}. At Komarno, the average recruitment in the T0 treatment was 5.1 (±1.64) plants m^{-2}, which was significantly lower than recruitment in the T1 and T2 treatments. The fall recruitment at Komarno followed the same trend in response to tillage as did the spring recruitment, where recruitment was greater in tilled treatments relative to untilled treatments. An interesting effect was observed when comparing the extent of false cleavers emergence between tillage treatments for the fall 2001 versus the spring 2001 experiments. In the spring of 2001, emergence levels for the fall tillage only (T1) treatment were similar to the emergence levels for the untilled (T0) treatment. This was expected, because in the spring 2001 experiments, the T1 and T0 treatments were the same treatment. However, after only a single tillage operation in the fall of 2001, emergence counts in the T1 treatments were similar to those in the T2 treatment,

Table 4-2. Mean gravimetric moisture (%) at Petersfield and Komarno, MB averaged over all measurement days in June 2001 (for the spring 2001 experiment), September-October 2001 (for the fall 2001experiment) or June 2002 (for the spring 2002 experiment and for the over-wintering experiment) as affected by tillage treatments; no additional tillage after the start of the experiment (T0), one fall tillage operation only (T1) and one spring and one fall tillage operation (T2[a]).

	Petersfield				Komarno			
Factor	Spring 2001[b]	Fall 2001[b]	Spring 2002	Over-wintering	Spring 2001	Fall 2001	Spring 2002	Over-wintering
Tillage								
T0	45.74a[c]	29.16a	44.43a	45.52a	24.59a	20.29a	23.93a	22.73a
T1	-	28.90a	-	45.53a	-	19.78ab	-	21.34a
T2	46.75a	28.91a	44.35a	46.91a	24.27a	19.63b	23.57a	22.02a
LSD	1.526	0.8.42	1.426	1.412	1.020	0.660	0.540	1.424

[a]For the spring 2001 and spring 2002 experiments, the T2 treatment would include a single tillage operation in the given spring. For the fall 2001 experiment, T2 would include one spring 2001 tillage operation and one fall 2001 tillage operation. For the over-wintering experiment, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.

[b]At Petersfield in the spring 2001 experiment and the fall 2001 experiment there was a significant date x tillage interaction. Repeated measures analysis is discussed in the text; see 4.3.3(i) and 4.3.3(ii). Results presented in the table were determined using an analysis of variance (PROC GLM).

[c]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

suggesting that a portion of the false cleavers seeds spread on the soil surface in the spring of 2001 remained non-dormant or became non-dormant and were able to recruit after fall tillage, possibly due to seed burial.

The absence of a tillage treatment effect on fall recruitment levels at Petersfield was likely due to the generally low recruitment levels, which made it difficult to detect treatment effects. Even though recruitment was low at Petersfield, the trend of tillage effect on emergence level was the same as observed in Komarno.

Very low recruitment in the fall relative to the spring may have been associated with environmental conditions that were unfavorable for recruitment, including low air temperature and precipitation levels. Low recruitment may have also been related to dormancy induction. We suspect that the false cleavers seedlot used in our experiments conformed to a typical summer annual growth habit (See 4.1.3(i)). Species that possess a summer annual growth habit have dormancy cycles enabling them to emerge during the spring period only. For summer annuals, low winter temperatures act to alleviate dormancy in preparation for spring germination, whereas, high summer temperatures induce dormancy so that germination prior to unfavorable winter conditions is avoided (Benech-Arnold et al. 2000).

4.2.2(iv) The Impact of Winter Seed Weathering on False Cleavers Recruitment

In the spring of 2002, false cleavers emergence in the over-wintering experiments was low relative to the spring 2002 experiments. There were no significant differences in false cleaver emergence between tillage treatments in either the augmented or non-augmented treatments in the over-wintering experiment, at either site (Table 4-1).

However, the number of observations made per treatment was also small (N = 4 or 5), thus, our ability to detect treatment differences was limited. The mean recruitment levels for the tillage treatments did not show a consistent trend between sites, or between the augmented and non-augmented treatments. However, if you consider only the T0 and T2 treatments, average recruitment in the untilled treatment was greater than average recruitment in the tilled treatment in the augmented and non-augmented treatments in Petersfield and the non-augmented treatments in Komarno. Spring 2002 emergence averaged over all tillage treatments for the non-augmented treatments in the over-wintering experiment was only 28 (±4.8) plants m^{-2} and 12 (±2.7) plants m^{-2} for the Petersfield and Komarno sites, respectively. In the treatments that did not receive any additional cleavers seed in the fall of 2001 (non-augmented), the lower level of recruitment will, in part, be associated with a reduction in the available seed bank as a result of previous recruitment. However, in our experiment the number of seeds recruited in the spring and the fall of 2001 was low relative to the number of seeds present in the soil seedbank. Thus, it is unlikely that the reduced level of recruitment that took place in the over-wintering experiments in the spring of 2002 was related to the exhaustion of seedbank reserves. For subplots which received additional cleavers seed in the fall of 2001 (augmented), the average spring 2002 recruitment level for all tillage treatments and both sites combined was 90 (±7.3) plants m^{-2}. In the augmented treatments, the reasons for reduced recruitment in the over-wintering experiments compared to the spring 2002 experiments are not as obvious. One of the main differences between the conditions experienced by the cleavers seed in the spring 2002 experiments relative to the over-wintering experiments was the exposure to winter weathering conditions. Winter periods

can affect seed viability. An experiment investigating the seed dynamics of meadow salsify (*Tragopogon pratensis* L.), showed that the rate of seed mortality was greatest during the months of October to May (Meiquin et al 1996). This study took place in central British Columbia, where temperatures are more moderate than in Manitoba, however, the average monthly air temperature in this region did fall below zero for approximately five months during the study (Meiquin et al. 1996). They identified predation, seed decay and suicidal germination as possible causes for the enhanced mortality rate during the winter period.

The level of seed predation, decomposition and suicidal germination that took place during our experiment was not measured. However, as in the Meiquin et al. (1996) study, seed predation, decomposition and suicidal germination occurring over the winter may have led to a reduction in the cleavers seedbank. Seed predation can affect weed seed number in all tillage treatments; however, the greatest effect would likely be on the untilled experiments (T0), due to the predominant surface placement of seeds (See 3.2.3). Seed spread onto the soil surface in the fall of 2001 would have made these seeds vulnerable to predation by insects and mammals for the months leading up to snow fall. Experiments investigating the impact of seed predation on seed numbers indicate that the removal of seeds by vertebrate and invertebrate predators can be significant. From a total of 60 seeds of the perennial tussock grass species *Ampelodesmos mauritanica* (Poiret), approximately half were removed after only a single day on the soil surface, with maximum removal occurring after approximately 20 days (Vola and Lloret 2000). Variation in the rate and extent of seed removal depended on variation in site and season chararcteristics. Small birds, mammals and insects, specifically ants, were identified as

the most likely predators of surface seeds in this experiment (Vola and Lloret 2000). Menalled et al. (2000), investigated weed seed predation during the month of September in southern Michigan crop fields. In this experiment, weed seeds were placed on the soil surface and their removal over time was recorded. Based on observations made over 7 days, approximately 13% of weed seeds placed on the soil surface were removed per day (Menalled et al. 2000). This rate included the combined effects of invertebrate and vertebrate predation, as well as, non-predation loses (natural forces). Menalled et al. (2000) also observed that the predator community was non-selective in terms of weed species. They considered four weed species of varying seed size in their trial; crabgrass (*Digitaria sanguinalis*), giant foxtail (*Setaria faberii*), redroot pigweed (*Amaranthus retroflexus*) and velvetleaf (*Abutilon theophrasti*). The seed size and shape of redroot pigweed (1-1.2mm) is most representative of false cleavers (1.5mm). During the course of our experiment, no observations were made of the extent of seed predation. However, the presence of a treed refuge area adjacent to the field, and the observation of birds and insects at both sites, would suggest that seed removal by vertebrate and invertebrate predators would have been possible.

Loss of viability, and seed decomposition associated with the action of soil microbes, would also reduce the amount of false cleavers seed available for recruitment in the experiments in which seed was allowed to over winter. Seed death resulting from decomposition would likely be less of a factor in the untilled experiments relative to the tilled experiments (T1 and T2) where the majority of seeds were below the soil surface, and thus, in greater contact with the soil matrix and the associated microbial community. Observations made during initial false cleavers germination tests suggest that false

cleavers seed can be colonized by microbial pathogens. False cleavers seed viability was not directly tested. Thus, we were unable to speculate if microbes colonized seeds that were already dead, or if colonization led to seed mortality.

Suicidal germination occurs when a seed germinates at a depth from which the shoot will not reach the soil surface prior to exhausting the seeds energy reserves. Seedling death resulting from suicidal germination may or may not have occurred in our experiment. Research suggests that the occurrence of seed mortality by these means is rare. Benvenuti et al. (2001), tested 20 weed species and found that in approximately 85% of weed species excessive burial depth will result in dormancy and not suicidal germination. In their study *G. aparine* was found to emerge from depths as great as 10cm. They found that deeper burial led to depth mediated-dormancy, not suicidal germination (Benvenuti et al. 2001). In our experiment, we would not expect many false cleavers seeds to be located beyond the depth of cultivation (approximately 7cm below the soil surface). *G. spurium* seed tends to be smaller than *G. aparine*, suggesting that *G. spurium* may not be able to recruit from depths as great as those from which recruitment of G. aparine is possible. Malik and Vanden Born (1988), suggest an optimum depth of 0.5cm for *G. spurium* recruitment. They do not suggest a maximum depth of recruitment for this species. Boyd and Van Acker (2003), showed that cleavers recruitment was maximized between 1 and 4cm depth, and recruitment was possible from 6-7cm depth, however, it was greatly reduced.

4.2.2(v) Residue Effects on Recruitment

Though stubble measurements were not done in the fall of 2001, the amount of residue cover present would be equal to or greater than that which was measured in the spring of 2002 on the over-wintering experiment. The presence of wheat residues on the surface of the subplots, especially the untilled subplots could have affected the level of recruitment that occurred in the fall of 2001 and in the spring of 2002 in the over-wintering experiments. Seeds located on the soil surface may have been shaded by the build up of residue on the surface. However, Malik and Vanden Born (1997c) showed that false cleavers germination is sensitive to the exposure to even low light intensities. In their trials, germination was reduced by 15% and 40% after 7 days of exposure to 6 and 12μE m^{-2} s^{-1}, respectively. Comparing these light intensities to that encountered on a typical clear summer day in the northern hemisphere (2400μE m^{-2} s^{-1}), one can see just how sensitive false cleavers germination is to light. In the field, duration and intensity of light exposure would vary depending on the time of year and weather conditions. However, in all cases exposure would be intermittent due to the occurrence of dark night periods. Malik and Vanden Born (1997c) showed that no germination occurred when false cleavers seeds were subjected to 1 hour of exposure to light at an intensity of 450 μE m^{-2} s^{-1}after 3, 7 or 11 hours of darkness, cycled over 8 days. If the level of solar radiation reaching the imbibed seeds is sufficiently reduced by the presence of residues, the proportion of seeds induced into secondary dormancy would be less compared to residue-free areas. This would increase the potential spring 2002 recruitment, specifically in the untilled treatment in the over-wintering experiments. This, however, did not occur in our study where tillage, and the associated surface residue cover, did not

significantly affect recruitment in the over-wintering experiments (Table 4-1). However, apart from the augmented treatments in the over-wintering experiment at Komarno, there was a trend towards greater recruitment in the T0 treatment relative to the T2 treatment. It is not clear whether the enhanced recruitment in the T0 experiment was associated with the impact of residues on seed shading, because if residue induced shading was causing enhanced recruitment in the T0 treatments, we would have anticipated that recruitment levels occurring in the T0 treatments would be similar to or slightly less than the level of recruitment occurring in the T2 experiments, where seeds were buried by tillage action.

In some cases, the presence of residue on the surface has been shown to influence soil moisture and temperature conditions, especially near the soil surface. Blevins et al. (1971) suggested that the presence of residues on the soil surface causes an increase in soil moisture levels largely by reducing evaporation and increasing infiltration. In our experiment, the soil volumetric moisture measured in the spring of 2002 at three soil depths was significantly greater in the untilled treatment (T0) relative to the tilled treatments (T1 and T2) in the over-wintering experiment at Komarno (Table 4-6). At Petersfield in the spring of 2002, we did not find significant differences in volumetric moisture between tillage treatments in the over-wintering experiment. However, the trends were similar at both Petersfield and Komarno. When gravimetric soil moisture was measured in the over-wintering experiments, no significant tillage treatment effects were apparent at either site. This emphasized the importance of proper measurement scale. Gravimetric soil moisture sampling consisted of a composite sample taken from 0-6cm, and resulted in no treatment effect. The volumetric soil moisture measurements were taken at a finer scale (0-2, 2-4, 4-6cm) treatment differences were captured.

If soil moisture levels increase with the presence of surface residues, soil temperature may be indirectly affected. Burke and Upchurch (1995) noted that moist soils tend to be cooler than dry soils. Also, residues may affect soil temperature levels more directly, by increasing the amount of solar radiation reflected from the surface. Moroizumi and Horino (2002) recorded temperature increases of 1.6°C on the surface, and 1.0 °C at 4cm, in tilled versus untilled treatments. Potter et al. (1985) observed that surface residue cover had a greater affect on soil temperature than the thermal properties of the soil. In our experiment, measurements taken at 4cm depth in Petersfield and Komarno in the over-wintering experiments did show a significant tillage treatment effect, however, the actual differences in temperature between treatments were very small (Table 4-3). The tilled treatments tended to be slightly warmer than the untilled treatment. The average difference in soil temperature between the tilled and untilled treatments was 0.09°C and 0.22°C at Petersfield and Komarno, respectively. Based on this, we suggest that the presence of residues was not likely generating biologically meaningful differences in soil temperature conditions between tillage treatments. This may be an effect of the short duration of the experiment. Residues only accumulated over a single season, thus, changes in soil conditions often associated with residues may not have had an opportunity to develop.

4.2.3 Influence of Tillage on Simulated Weed Seed Position in the Soil Profile

As was the case for seedling recruitment, simulated seed placement dynamics were investigated in the short and long term. Seed placement simulation experiments were initially established in the fall of 2001 at both sites. Subsequently, new experiments

were established in the spring of 2002 at both sites. The experiments established in the fall of 2001 were observed again in the spring of 2002 to investigate the impact of an over-wintering period on seed placement. Observations were made on the over-wintering experiments both pre and post cultivation in the spring of 2002.

4.2.3(i) Influence of a Single Tillage Operation on Bead Placement

Surface bead counts indicated that a greater proportion of beads remained on the surface in untilled versus tilled treatments (Table 4-4). At Komarno, the number of beads counted on the soil surface was unexpectedly high in the fall 2001 experiment (run 1). Using the weight of beads spread per subplot (150g), the size of each experiment plot ($5m^2$) and the 100 bead weight (0.93g) one would expect a maximum count of approximately 3200 beads m^2. Having counts higher than 3200 beads m^2 suggests that the beads may not have been spread evenly over the soil surface. Uneven bead spread may be associated with differences in surface characteristics both within the experiments at a given site, and between the two sites. Within the experiments, beads would accumulate more readily in depressions, regions with rough surfaces and/or on extremely level areas. More beads remained on the surface at Komarno versus Petersfield in both the tilled and untilled treatments. The surface at Komarno captured more beads largely because it was extremely level, and essentially free from cracks. The soil surface at Komarno was smooth relative to Petersfield, however, it did have some roughness. The surface was patterned with small soil undulations which were sufficient to trap beads, given that the soil surface was very level. At Petersfield, we would have anticipated that the greater surface roughness would have led to increased bead capture relative to

Table 4-3. Average daily maximum (max), minimum (min) and/or mean soil temperature (°C) measured at 1cm and 4cm, at two sites, Peterfield and Komarno, MB, for the spring 2001 experiment (measured in spring 2001), spring 2002 experiment (measured in spring 2002), fall 2001 experiment (measured in fall 2001) and over-wintering experiment (measured in spring 2002), as affected by two or three tillage treatments; T0, no additional tillage after the start of the experiment; T1, one fall tillage operation only and T2[a], one spring and one fall tillage operation.

		Petersfield						Komarno						Pooled[d]
			Spring 2001		Spring 2002[b]	Fall 2001[c]	Over-wintering		Spring[i] 2001		Spring 2002	Fall 2001	Over-wintering	Spring 2002
Factor		Max	Min	Mean	Mean	Mean	Mean	Max	Min	Mean	Mean	Mean	Mean	Max
Tillage[e]	T0	24.83a[f]	16.27a	17.83a	18.70a	11.90a	17.46a	23.08a	16.46a	17.80a	18.30a	10.89a	18.06a	22.63a
(Temp. at 4cm)	T1	-	-	-	-	11.15b	17.53ab	-	-	-	-	10.65ab	18.15a	-
	T2	24.13b	16.31a	17.43b	18.56b	11.38c	17.57b	23.19a	16.59b	17.96b	18.25a	10.43b	18.41b	22.34b
LSD		0.160	0.041	0.132	0.123	0.114	0.105	0.170	0.062	0.145	0.065	0.260	0.129	0.280
Tillage[g]	T0	-	-	-	19.14a	-	19.04a	-	-	-	18.73a	-	19.12a	24.51a
(Temp. avg.	T1	-	-	-	-	-	19.06a	-	-	-	-	-	19.40a	-
of 1 and 4cm)	T2	-	-	-	18.93b	-	19.06a	-	-	-	18.67a	-	19.40a	23.97b
LSD		-	-	-	0.122	-	0.140	-	-	-	0.078	-	0.331	0.267
Depth[h]	1	-	-	-	19.44a	-	19.48a	-	-	-	19.12a	-	19.71a	25.99a
	4	-	-	-	18.63b	-	18.62b	-	-	-	18.28b	-	19.90b	22.48b
LSD		-	-	-	0.122	-	0.114	-	-	-	0.078	-	0.271	0.267

[a] For the spring 2001 and spring 2002 experiments, the T2 treatment would include a single tillage operation in the given spring. For the fall 2001 experiment, T2 would include one spring 2001 tillage operation and one fall 2001 tillage operation. For the over-wintering experiment, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.

[b] Maximum and minimum soil temperatures for the over-wintering experiments and minimum temperature for the spring 2002 experiment are presented in Table 4-7, as a result of significant depth x tillage interactions or pooling.

[c] Maximum and minimum soil temperatures were not determined for the fall 2001 experiment.

[d] For maximum soil temperature sites were insignificant on the spring 2002 experiments, therefore data presented are pooled between sites.

[e] Average (avg.) soil temperature (temp.) at 4cm below the soil surface.

[f] Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

[g] Mean soil temperature averaged between 1cm and 4cm below the soil surface.

[h] Average (avg.) soil temperature (temp.) at two depths, measured in 2002 only, averaged for two (spring 2002 experiment) or three (over-wintering experiment) tillage treatments.

[i] In the spring 2002 experiment at Komarno, there was a significant date x tillage interaction identified for the mean soil temperature at 4cm. Repeated analysis was subsequently done to identify significant dates. Results presented in the table were determined using an analysis of variance (PROC GLM).

Komarno. However, due to the extensive soil surface cracking at Petersfield, a large proportion of beads were moved from the surface into these cracks where they were lost.

In the spring 2002 experiment (run 2), more beads were found on the surface in untilled treatments versus tilled treatments (Table4-4). However, the total number of beads on the surface at Komarno did not exceed the expected maximum and was lower than at Petersfield. The reduced number of beads on the surface at Komarno in run 2 relative to run 1 may have been related to the windy conditions during bead spreading in the spring of 2002. The Komarno spring 2002 simulated seed placement experiment was situated at the end of a large open field which received no shelter from the wind. It was very windy during bead spread in the spring of 2002. A proportion of beads would have likely been blown beyond the bounds of experiments prior to counting. The Petersfield spring 2002 simulated seed placement experiment was located in a relatively sheltered area.

4.2.3(iii) Influence of Over-wintering on Bead Placement

Bead surface counts were conducted on the over-wintering simulated seed placement experiments in the spring of 2002 (Table 4-4). Counts were conducted prior to any additional tillage operations in the spring of 2002. The results showed that at both sites and within tillage treatments a proportion of the beads that were on the surface in the fall of 2001 were either taken to greater depths within the soil profile by freeze thaw action, or moved beyond the bounds of the experiments by wind or snow melt. Counts indicated that a relatively high proportion of beads were lost from the soil surface over

Table 4-4. Average number of beads present on the soil surface at two sites, Peterfield (Pfld) and Komarno (Kom), MB as affected by tillage treatment; one pass with a sweep cultivator (tilled) and no disturbance after bead spread (untilled), counted immediately after applying the tillage treatments (run 1, fall 2001 experiment and run 2, spring 2002 experiment), counted after a winter period prior to a second spring cultivation operation (over-wintering experiment pre-cultivation) and counted after a winter period and a second tillage operation (over-wintering experiment post-cultivation).

	Run 1 Fall 2001 Experiment		Run 2 Spring 2002 Experiment		Over-wintering Pre-cultivation		Over-wintering Post-Cultivation	
Factor	Pfld	Kom	Pfld	Kom	Pfld	Kom	Pfld	Kom
Tilled	64(±8)[a]	176(±28)	128(±21)	95(±18)	28(±4)	95(±21)	63(±12)	88(±14)
Untilled	2336(±213)	4224(±376)	2243(±98)	1982(±160)	840(±73)	2360(±160)	711(±82)	1843(±163)

[a]Standard error of the treatment means.

winter. This would suggest that for false cleavers, a large proportion of seed present on the surface in the fall of 2001 would be moved to greater depths over the winter season. However, false cleavers recruitment levels recorded in the spring of 2002 on the over-wintering recruitment experiments do not support this theory.

4.2.3(ii) Impact of Over-wintering and a Second Tillage Operation on Surface Bead Placement

Approximately one month after the pre-cultivation surface counts of beads in the spring of 2002 on the over-wintering simulated seed placement experiments, the tilled treatments were cultivated again, and post cultivation counts were done. In three of four treatment-site combinations the number of beads on the surface was reduced relative to pre-cultivation counts (Table 4-4). When compared to the spring 2002 counts in the over-wintering experiments prior to cultivation, the number of beads that remained on the surface after the second tillage operation were reduced by by 7% in the tilled treatment at Komarno. Even where not additional tillage the surface bead counts were reduced by 15% in the untilled treatment at Petersfield and by 22% in the untilled treatment at Komarno. A reduction in the surface bead counts in the untilled treatment may have been due to weathering, including bead movement associated with rain impact and wind. Weathering may move beads horizontally where they could fall into soil cracks or be moved beyond the bounds of the experiment. Both wind and rain can also dislodge surface soil particles leading to bead burial. In the tilled treatment at Petersfield there were 25% more beads on the soil surface after cultivation. Soil inversion during tillage brought previously buried beads back to the soil surface. Chisel plowing has been shown to redistribute weed seeds relatively evenly within the tillage zone, including on the soil

surface (Yenish et al. 1996). The same affect was not observed at Komarno. The differences between sites may have been due to differences in soil texture and how this affects the degree of soil inversion occurring during tillage. In Petersfield, the soil had a fine clay texture with a massive structure that led to the formation of large soil clods. Tillage of this soil broke apart clods and moved those clods which were located deeper in the cultivation zone back to the soil surface. Beads contained within or fixed to these clods were then exposed at the soil surface. In Komarno, the silt loam soil with a fine platy structure did not form distinct soil clods. Tillage of this soil redistributed beads within the tillage zone; however, fewer beads resurfaced. We believe that because the beads were heavier and larger than soil particles, and the soil at Komarno was quite loose, the majority of beads simply sank below the smaller soil particles during tillage.

In all cases, the number of beads on the surface in the untilled treatments far exceeded the number of beads present on the surface in the tilled treatments. Thus, it can be said that the experiments which remained untilled throughout the experiment would likely have had a greater number of cleavers seeds remaining on the soil surface than the experiments which where tilled. Surface locations are considered unfavorable for false cleavers seedling recruitment (Malik and Vanden Born 1997c).

4.2.3(iv) Bead Location Within the Soil Profile

In the spring of 2002, measurements were made to investigate the placement of beads at three depths (0-2, 2-4, 4-6cm) in the experiments initiated in the spring of 2002. Counts indicated that soils of the untilled treatments contained the greatest proportion of beads at the shallowest depth. The number of beads found at 0-2, 2-4 and 4-6cm in the

untilled treatments were 0.467, 0.002, 0.000 beads cm^{-3}, and 0.280, 0.002, 0.000 beads cm^{-3} for Petersfield and Komarno, respectively. The number of beads measure at 0-2, 2-4 and 4-6cm for the tilled treatments were 0.098, 0.032, 0.004 beads cm^{-3} and 0.155, 0.019, 0.000 beads cm^{-3} for Petersfield and Komarno, respectively. Thus, even though tillage removed the beads from the soil surface, it did not move the beads very deep into the soil profile. In fact, the majority of beads were moved from the surface and placed no deeper than 4cm. One of the major factors known to limit cleavers recruitment is the prolonged exposure of imbibed seeds to solar radiation (Malik and Vanden Born 1997c). It is generally accepted that light can only penetrate the soil up to 1 cm depth, though there is some variability associated with differences in clod size (Cussans et al. 1996; Meiqin et al. 1996). Thus, only a shallow soil cover is necessary to overcome limitations in false cleavers recruitment associated with light induced dormancy. Our results suggest that a single shallow (5-7cm) tillage event was sufficient to provide enough soil cover to prevent light exposure limitation of false cleavers recruitment.

4.3 Characterization of Seedling Recruitment Microsites

4.3.1 Soil Bulk Density

Soil bulk density measured for both the tilled and untilled treatments, showed that the average soil bulk density at Komarno was consistently higher than at Petersfield (Table 4-5). This was likely related to differences in soil texture between sites. The heavy clay soil at Petersfield is made up of greater proportion of fine particles (clay) than the silt loam textured soil at Komarno. Generally, soil bulk density increases with an increase in the proportion of coarser type materials (Haluschak 1987). As a result, the

bulk density of the soil at Petersfield, with fewer coarser particles, would be expected to be lower than at Komano. Average bulk density measured in the spring 2001 experiment, was significantly lower in the tilled treatment relative to the untilled treatment at Petersfield, but not at Komarno. No tillage treatment effect on soil bulk density was found at Komarno because the entire site had been cultivated by the land owner only days prior to the start of the trial. Thus, the cultivation performed as part of the experiment would not have likely changed the soil bulk density.

At Komarno in the fall of 2001, there was a significant difference in soil bulk density between the untilled (T0) and the tilled treatments (T1 and T2). There was no significant difference in soil bulk density between the T1 and the T2 treatments (Table 4-5). Cultivation loosened the soil leading to reductions in bulk density relative to untilled treatments. At the Komarno site, the silt loam textured soil was easily tilled. No clod formation occurred during tillage, and after tillage was complete the soil surface appeared relatively even and consistent. At Petersfield, fall soil bulk density did not differ significantly between tillage treatments. Due to the heavy clay texture of the soil, tillage was difficult at this site. The cultivator sweeps did not consistently penetrate the soil, leaving some areas untilled and many large clods unbroken. As a result, the condition of the soil on much of the surface of the tilled treatments was similar to that of the untilled treatments. This may partially explain why there were no significant differences in soil bulk density between tillage treatments in the fall at Petersfield. However, the relationship between tillage intensity and bulk density is not always consistent. Some experiments have documented bulk density changes with tillage (Kettler et al. 2000; Xu

Table 4-5. Average soil bulk density (g cm^{-3}) at two sites, Peterfield and Komarno, MB in the spring 2001 experiments (measured in spring 2001), spring 2002 experiments (measured in spring 2002), fall 2001 experiments (measured in fall 2001) and the over-wintering experiments (measured in spring 2002), as affected by two or three tillage treatments; T0, no additional tillage after the start of the experiment T1, one fall tillage operation only and T2, one spring and one fall (fall 2001 experiment only) tillage operation and sampling depth; 0-2, 2-4 and 4-6 cm (spring 2002 and over-wintering experiments only).

		Petersfield				Komarno			
Factor		Spring 2001	Fall 2001	Spring 2002	Over wintering	Spring 2001	Fall 2001	Spring 2002	Over-wintering
Tillage	T0	0.88(±0.012)[a]a[b]	0.96(±0.013)a	1.00(±0.031)a	0.94(±0.058)a	1.16(±0.022)a	1.26(±0.085)a	1.23(±0.034)a	1.26(±0.063)a
	T1	-	0.95(±0.017)a	-	0.97(±0.028)a	-	1.18(±0.091)b	-	1.18(±0.048)a
	T2	0.78(±0.072)b	0.96(±0.014)a	0.95(±0.058)a	0.91(±0.023)a	1.18(±0.022)a	1.13(±0.098)b	1.27(±0.034)a	1.29(±0.053)a
LSD		0.035	0.042	0.119	0.071	0.062	0.061	0.095	0.150
Depth (cm)	0-2	-	-	0.87(±0.051)a	0.82(±0.035)a	-	-	1.14(±0.045)a	1.12(±0.029)a
	2-4	-	-	0.98(±0.033)ab	0.94(±0.028)b	-	-	1.25(±0.039)b	1.28(±0.055)b
	4-6	-	-	1.07(±0.031)b	1.06(±0.013)c	-	-	1.37(±0.009)c	1.34(±0.040)b
LSD		-	-	0.146	0.071	-	-	0.117	0.150

[a]Standard error of the treatment means

[b]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

and Mermoud 2001) others have observed no difference in bulk density with tillage (Potter et al. 1985). Differences in soil texture and year to year variation in environmental conditions, specifically soil moisture, affect the response of soil bulk density to changing tillage intensities. The inconsistencies expressed in previous experiments and the differences observed between sites in our experiment reinforce how variable the relationship between soil bulk density and tillage can be.

Differences in soil bulk density between tillage treatments occurred in the spring 2001 experiment at Petersfield and the fall 2001 experiment at Komarno. Many experiments have shown that increasing soil bulk density causes a decrease in seedling recruitment (Charles et al. 1991; Thill et al. 1979). However, this response is species specific and can vary with soil type, soil moisture and the extent of the bulk density increase. Increased bulk density levels can negatively affect seedling recruitment by inhibiting the diffusion of soil gases, hindering soil water transport, or increasing the penetration resistance of the soil (Benvenuti et al. 2001; Pereja and Staniforth 1985). No research has been done to determine the sensitivity of false cleavers recruitment to soil bulk density. Thus, it is not known if soil resistance levels that are restrictive to false cleavers recruitment were achieved in our experiments. Other studies have shown that increases in bulk density may actually enhance weed seedling recruitment (Boyd 2003; Thomas and Zhang 1999). A change in bulk density from 1.20 g cm^{-3} to 1.31 g cm^{-3} achieved by compaction with a roller resulted in an increase in seedling recruitment for a number of different weed species (Boyd 2003). Enhanced recruitment is believed to be associated with better soil-seed contact and improved soil water uptake by the seed. In our experiment, bulk density was significantly greater in the untilled treatments relative

to the tilled treatments in the spring 2001 experiment at Petersfield and in the fall 2001 experiment at Komarno. During the same periods we did not see enhanced recruitment levels in the untilled experiments. We suspect that bulk density differences were not greatly impacting false cleavers recruitment, negatively or positively, because there does not appear to be a consistent trend in the response of seedling recruitment to bulk density variation. Factors other than soil bulk density were likely influencing recruitment.

4.3.1(i) Bulk Density Variation with Depth

Soil bulk density measures done in the spring of 2002, were taken at three depths; 0-2, 2-4 and 4-6cm (Table 4-5). There were no significant differences in soil bulk density between tillage treatments at either site, in either year. Though there was no significant tillage treatment effect on soil bulk density, there was a significant soil depth effect on soil bulk density at both sites in the spring 2002 experiments and the over-wintering experiments. In general, soil bulk density increased with increasing depth. This has been observed by other researchers. Haluschak (1987) measured greater bulk densities at 15-60cm relative to 0-15cm in five soil textural groups ranging from those consisting primarily of coarse to fine particles. At Komarno, in the spring 2002 experiment, the soil bulk density increased significantly from 0-2cm to 4-6cm. At Petersfield, in the spring 2002 experiment, the trend remained the same, however, significant differences in soil bulk density were only seen between the 0-2cm and 4-6cm depths. At Komarno, in the over-wintering experiment there was an increase in soil bulk density with depth, however, significant differences occurred only between the 0-2cm and 2-4cm depths, and the 0-2cm and 4-6cm depths. At Petersfield in the over-wintering

experiment the soil bulk density was significantly greater at 4-6cm relative to 0-2cm. Though in our experiment the relationship of increasing soil bulk density with depth was not always evident within each incremental change in depth (0-2 to 2-4 to 4-6cm), there was a consistent difference between the bulk density at 0-2cm and the 4-6cm depth.

4.3.2 Soil Temperature

4.3.2(i) Spring Soil Temperature

Mean daily soil temperature measured in the spring experiments in 2001 and 2002 at 4cm was significantly different between tillage treatments in three of four site years (Table 4-3). In the spring 2001 and spring 2002 experiment at Petersfield the mean soil temperature at 4cm was slightly greater in the untilled treatment relative to the tilled treatment. This is the opposite of the results found for the spring 2001 experiment in Komarno, where the mean soil temperature at 4cm was slightly greater in the tilled treatment relative to the untilled treatment. In the spring 2002 experiment at Komarno, no significant differences in mean soil temperature at 4cm were recorded. However, a significant date x tillage treatment interaction was identified in the analysis of the data for mean soil temperature at 4cm at Komarno in the spring 2002 experiment. Repeated measures analysis identified a significant tillage treatment effect in 3 of 28 days. However, in all cases where soil temperature was significantly different between tillage treatments, including the three days in the spring 2002 experiment at Komarno, the differences were very small. The differences in mean soil temperature at 4cm between tillage treatments were 0.4°C , 0.14°C and 0.16°C for the spring 2001 experiment at Petersfield, the spring 2002 experiment at Petersfield and the spring 2001 experiment at

Komarno, respectively. Such small differences in temperature would not likely have caused the differences in false cleavers recruitment that were observed between the tillage treatments in the spring period. However, a statistically significant difference may not necessarily translate into a biologically significant difference. If we calculate the difference in growing degree days (GDD) between the tillage treatments for experiments where significant differences were found in the spring, there was an average of 0.25 GDD/day difference between the tilled and untilled experiments. If we consider the accumulation in GDD taking place over a 75 day emergence period, this equals a total of 19 GDD difference between tillage treatments. Using wild oat emergence as a biologically and practically meaningful measure of this difference, we see that, if the rate of maximum emergence for this species is 0.29% of total emergence per GDD, the difference in GDD between the tillage treatments would represent 5% of total expected wild oat emergence in a given spring emergence period (Bullied et al. 2003). Thus, the soil temperature difference between tillage treatments is not likely driving the observed differences in cleavers recruitment between the tillage treatments. The statistically significant difference may merely be a reflection of the very high number of observations ($n = 150$) included in the analysis and the resulting high discrimination power, rather than the existence of a biologically meaningful difference between treatments.

Daily mean soil temperature at 4cm in the over-wintering experiments was found to vary between tilled and untilled treatments (Table 4-3). At Komarno, mean daily soil temperature for the T2 treatment was significantly greater relative to either the T1 or T0 treatments. Soil temperatures were not significantly different for the T0 and T1 treatments in the over-wintering experiments at Komarno. At Petersfield, in the over-

wintering experiment, mean soil temperature at 4cm was only significantly different between the T0 and T2 treatments. The difference in the average soil temperature between the T2 and T0 treatment measured at 4cm in the over-wintering experiments was only 0.11°C and 0.35°C at Petersfield and Komarno, respectively. Soil temperature differences this small would likely not influence false cleavers recruitment.

4.3.2(ii) Soil Temperature Fluctuations

The soil temperature tables were divided based on the presence or absence of significant depth x tillage treatment interactions. Average daily maximum and minimum soil temperatures recorded in the spring periods are shown in Tables 4-3, 4-6 and 4-7. The relationship of maximum and minimum soil temperatures at 4cm is not consistent between sites. In the spring 2001 experiments, average daily maximum soil temperature was significantly different between tillage treatments at Petersfield but not at Komarno and average daily minimum soil temperature was significantly different between tillage treatments at Komarno, but not at Petersfield (Table 4-3). In the spring of 2002, average daily maximum temperature at 4cm, averaged over both sites, was significantly greater in the untilled treatment relative to the tilled treatment. This was also the case in the pooled spring 2002 experiments (pooled across sites) where the maximum soil temperature was averaged over 1cm and 4cm depth. Greater maximum temperatures in the untilled treatment were also found at Petersfield in the spring 2001 experiment. This is the opposite of what was found by Bullock and Lafond (2002) at Indian Head, SK. They recorded greater maximum temperatures at 5cm in tilled experiments relative to untilled experiments. In our experiment, only in the spring 2001 experiment at Komarno were the

average daily maximum temperatures greater in the tilled treatment relative to the untilled treatment. Bullock and Lafond (2000) also recorded lower minimum temperatures at 5cm in untilled versus tilled treatments. In our experiment, though there were not always significant tillage treatment effects, the average daily minimum temperature at 4cm was consistently lower in the untilled treatments relative to the tilled treatments. In the over-wintering experiment at Komarno, the minimum soil temperature at 4cm was lowest in the T0 treatment, moderate in the T1 treatment and highest in the T2 treatment (Table 4-6). This result is consistent with that obtained by Bullock and Lafond (2000). However, in all other in cases the over-wintering experiments there were no significant differences in maximum or minimum temperature between the T0 and T2 treatments, however, T0 and T2 treatments were consistently different than the T1 treatment. This result was unexpected. The reason for the significant difference in maximum and minimum temperature between the fall tilled treatment and the other two tillage treatments is not known.

Although there were significant differences in soil maximum and/or minimum temperatures at 4cm within certain experiments, average differences were quite small. For example, in the spring 2001 experiment, the difference in minimum temperature between tilled and untilled treatments at Komarno was only 0.13°C. The temperature differences recorded during the spring would be considered minor in biological terms. We suspect that differences this small would have had little influence on false cleavers recruitment.

The impact of greater maximum or lower minimum temperatures on cleavers recruitment is unknown. In our experiment, the seed used during spring false cleavers

Table 4-6.[a] Average daily maximum (max) and minimum (min) soil temperature (°C) at 1cm and 4cm, at two sites, Peterfield and Komarno, MB, for the pooled spring 2002 experiment (measured in the spring of 2002) data and over-wintering experiment (measured in spring of 2002) data, as affected by two or three tillage treatments; T0, no additional tillage after the start of the experiment; T1, one fall tillage operation only and T2[b], one spring and one fall tillage operation.

	Petersfield Over-wintering				Komarno Over-wintering				Pooled[c] Spring 2002	
	Max		Min		Max		Min		Min	
Factor	1cm	4cm	1cm	4cm	1cm	4cm	1cm	4cm	1cm	4cm
Tillage T0	26.45a[d]	23.35a	14.07a	14.62a	25.84a	23.54a	14.59a	15.30a	13.92a	14.48a
T1	26.58a	22.68b	14.01ab	14.97b	27.62b	23.23b	14.32b	15.47b	-	-
T2	26.19a	23.44a	13.92b	14.72a	26.49a	23.50a	14.48c	15.63c	14.07b	14.88b
LSD	0.573	0.278	0.086	0.098	1.990	0.226	0.113	0.138	0.130	0.128

[a] Data were analyzed separately for each depth due to the occurrence of significant depth x tillage treatment effects.
[b] For the spring 2002 experiments, the T2 treatment would include a single tillage operation in the spring of 2002. For the over-wintering experiment, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.
[c]For minimum soil temperature sites were insignificant on the spring 2002 experiment, therefore data presented are pooled between sites.
[d]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

seeding was assumed to be non-dormant when applied. Based on the results of germination tests done prior to the distributing false cleavers seed on the field, this assumption seems reasonable (See 3.1.2). However, it is possible that extremes in temperature may impact the seed dormancy. The sensitivity of false cleavers to seed temperature variation in terms of the induction or removal of dormancy is not known. Examining the recruitment occurring in the various treatments in relation to the presence of significant differences in daily average maximum or minimum temperatures between tillage treatments, indicates that extremes in temperature do not appear to be significantly influencing the recruitment patterns observed. For example, in the spring 2001 experiment, average recruitment at Komarno and Petersfield did not differ significantly. However, the average daily maximum soil temperature differed between tillage treatments at Petersfield but not at Komarno, and the average daily minimum soil temperature differed between tillage treatments at Komarno, but not at Petersfield. One might conclude, therefore, that differences in temperature extremes between the tillage treatments were not likely contributing greatly to the recruitment differences between tillage treatments which were observed.

4.3.2(iii) Fall Soil Temperature

In the fall of 2001, daily average soil temperature at 4cm was significantly different among all three tillage treatments at Petersfield (Table 4-3). At Komarno, in the fall 2001 experiment, daily mean soil temperature at 4cm was significantly different for the T0 treatment relative to the T1 and T2 treatments. Average fall soil temperature at 4cm was not significantly different between the two tilled treatments (T1 and T2) at

Komarno. The differences in the soil temperature between the tillage treatments at Komarno were not as great as those observed at Petersfield. However, at both sites in the fall 2001 experiments, soil temperatures at 4cm in the untilled treatments were greater than in the tilled treatments. This suggests that tillage induced changes at the soil surface which affected soil thermal properties. This may have been associated with the combined affect of direct physical changes to the soil structure and changes in the percent soil residue cover.

4.3.2(iii) Influence of Depth on Soil Temperature

In the spring of 2002, daily maximum, minimum and mean soil temperatures were measured at two depths; 1cm and 4cm. Soil temperature measures at depth for the spring 2002 experiment (mean and maximum temperatures), and over-wintering experiments (mean temperatures only) are shown in Table 4-3. Soil temperature measures at depth for the spring 2002 experiment (minimum temperatures) and over-wintering experiments (maximum and minimum temperatures) are shown in Table 4-7. The data has been allotted to separate tables based on the presence or absence of significant depth x tillage treatment interactions. In all cases, soil temperature recorded at 1cm was significantly different from soil temperature at 4cm. Where date x tillage treatment interactions were identified repeated measures analysis was done to determine significance based on the analysis of individual days. According to this analysis, maximum soil temperature was significantly greater at 1cm relative to 4cm in 5, 7 and 11 of 28 days for the Komarno-T1, Komarno-T2 and Petersfield-T0 over-wintering experiments, respectively. Minimum soil temperature was significantly lower at 1cm relative to 4cm in 8, 9 and 11 of 28 days

in the Komarno-T2, Petersfield-T0 and Petersfield-T2 over-wintering experiments, respectively. Minimum soil temperature was also significantly lower at 1cm relative to 4cm in 25 of 28 days in the spring 2002 pooled-T2 experiment. Because soil temperature is in constant flux based on daily, monthly and seasonal changes in the level of radiant energy reaching the soil surface, variation in the extent of temperature differences occurring within a small change in depth would be expected. Where significant differences in soil temperature with depth were recorded, the relationship between soil temperature at 1cm and 4cm varied with measure (max, min, mean), site (Petersfield, Komarno) and experiment (spring 2002, over-wintering). At Petersfield in the spring 2002 experiment, mean soil temperatures were higher at 1cm relative to 4cm. However, at Komarno the opposite relationship was found for mean soil temperature in the spring 2002 experiment (Table 4-3). A similar result was recorded for the mean soil temperature in the over-wintering experiments. Mean soil temperatures in the over-wintering experiments were higher at 1cm relative to 4cm at Petersfield, and lower at 1cm relative to 4cm at Komarno. Differences in soil thermal properties and soil color between the two sites may have contributed to these opposing results. Maximum and minimum soil temperatures were not significantly different at Petersfield and Komarno in the spring 2002 experiments, therefore, the data from both sites was pooled. In the pooled spring 2002 experiment, the maximum soil temperature was significantly greater at 1cm versus to 4cm (Table 4-3). This was also true for the over-wintering experiments at both sites for all three tillage treatments (Table 4-7). In the spring 2002 experiment (pooled), the minimum soil temperature was significantly lower at 1cm versus 4cm (Table 4-3). Again, this relationship was consistent for all minimum soil temperature

measures. Thus, the amplitude of temperature fluctuations were attenuated with depth. This is typical of most soils (Reimer and Shaykewich 1980). The temperature differences occurring with depth were larger than the differences that were recorded between tillage treatments. For the spring 2002 experiments the difference in mean soil temperature between 1cm and 4cm was 0.81°C and 0.84°C at Petersfield and Komarno, respectively. This difference reflects both the variation in the average daily maximum soil temperature and the variation in the average daily minimum soil temperature occurring with depth. Differences in maximum temperatures between 1cm and 4cm tend to be larger than differences in minimum soil temperature between 1cm and 4cm. For the spring 2002 experiment (pooled) the average difference in soil temperature between 1cm and 4cm was 0.56°C, 0.81°C and 3.87°C for the T0-minimum, T2-minimum and maximum temperatures measurements, respectively.

4.3.3 Soil Moisture Content

4.3.3(i) Spring Gravimetric Soil Moisture

Analysis of the gravimetric soil moisture samples taken from 0 to 5cm indicates that soil moisture conditions did not vary significantly between tillage treatments at either site either in the spring 2001 experiments or in the spring 2002 experiments (Table 4-2). Of the four spring site years considered, only one showed a significant date x tillage treatment interaction. This occurred in Petersfield in the spring 2001 experiment. Repeated measures analysis identified only one of the four dates sampled as having a significant difference in soil gravimetric moisture level between tillage treatments. On June 12, 2001, the average gravimetric soil moisture levels were 34.07 (± 0.957) % and 29.00 (± 0.843) % in the tilled and untilled treatments, respectively. On this date,

Table 4-7.[a] Average daily maximum (max), minimum (min) and/or mean soil temperature (°C) at 1cm and 4cm, at two sites, Peterfield and Komarno, MB, for the spring 2001 experiment (measured in spring 2001), spring 2002 experiment (measured in spring 2002), fall 2001 experiment (measured in fall 2001) and over-wintering experiment (measured in spring 2002), as affected by two or three tillage treatments; T0, no additional tillage after the start of the experiment; T1, one fall tillage operation only and T2[b], one spring and one fall tillage operation.

	Petersfield Over-wintering						Komarno Over-wintering						Pooled[c] Spring 2002	
	Max			Min			Max			Min			Min	
Factor	T0[d]	T1	T2	T0[d]	T1[d]	T2[d]	T0	T1[d]	T2[d]	T0	T1	T2[d]	T0	T2[d]
Depth														
1	26.45a[e]	26.58a	26.19a	14.07a	14.01a	13.92a	25.84a	27.62a	26.49a	14.59a	14.32a	14.49a	13.92a	14.07a
4	23.35b	22.68b	23.44b	14.62b	14.97b	14.72b	23.54b	23.23b	23.50b	15.30b	15.47b	15.63b	14.48b	14.88b
LSD	0.371	0.565	0.587	0.080	0.146	0.133	0.938	0.433	0.297	0.148	0.170	0.104	0.140	0.117

[a] Data were analyzed separately for each tillage treatment due to the occurrence of significant depth x tillage treatment effects.
[b] For the spring 2001 and spring 2002 experiments, the T2 treatment would include a single tillage operation in the given spring. For the fall 2001 experiment, T2 would include one spring 2001 tillage operation and one fall 2001 tillage operation. For the over-wintering experiment, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.
[c]For maximum soil temperature sites were insignificant on the spring 2002 experiments, therefore data presented are pooled between sites.
[d]In the given site-experiment-temperature measure-tillage treatment combination, there was a significant date x tillage interaction. Repeated analysis was subsequently done to identify significant dates. Results presented in the table were determined using an analysis of variance (PROC GLM).
[e]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

therefore, the average soil moisture levels in the tilled treatments were greater than in the untilled treatments. This result suggests that during certain periods, differences in soil moisture between tillage treatments can occur. However, a significant difference for only one of four sampling dates implies that these differences are not the norm. Soil gravimetric moisture in the over-wintering experiments was not significantly different between tillage treatments at either Komarno or Petersfield.

4.3.3(ii) Fall Gravimetric Soil Moisture

At Komarno in the fall of 2001, tillage significantly affected gravimetric soil moisture levels (Table 4-2). At Komarno, soil gravimetric moisture averaged for T0 treatments was significantly greater than the T2 treatment in the fall 2001 experiment. Gravimetric soil moisture for T1 treatment was not significantly different from the T0 and T2 treatments. Unlike at Komarno, gravimetric soil moisture levels were not significantly different between tillage treatments at Petersfield in the fall 2001 experiment. However, a significant date x tillage treatment interaction was found in the analysis of variance. Subsequent repeated measures analysis indicated that of the seven measurement dates considered one showed a significant tillage treatment effect. This occurred on September 25, 2001, when the soil gravimetric moisture was significantly different between all tillage treatments. The mean soil gravimetric moisture at Petersfield in the fall 2001 experiment on September 25, 2001 was 34.03(±1.058), 29.87(±0.656) and 30.90(±0.994)% for the T0, T1 and T2 treatments, respectively. Interestingly, this tillage treatment effect occurred three days after a precipitation event. This may reflect

the transient nature of moisture differences between tillage treatments, and the fact that these may be highly dependant on the absolute moisture content within the soil.

In the fall of 2001, it is possible that the combined effects of low soil temperature and low soil moisture levels led to reduced cleavers recruitment. During this period, both soil temperature and gravimetric soil moisture levels were lower than in the spring of either 2001 or 2002. Fall soil temperatures were approximately 35% and 40% lower in Petersfield and Komarno, respectively, in the fall 2001 experiments versus the spring 2001 experiments. Fall 2001 gravimetric soil moisture levels were approximately 40% and 20% lower than spring 2001values, for Petersfield and Komarno, respectively. Even though soil moisture levels recorded in the fall were considerably lower than spring values, it is not clear if these lower moisture levels were low enough to impact the recruitment of false cleavers. Malik and Vanden Born (1988) showed that false cleavers germination is reduced at moisture levels below -2.5 bars and prevented at levels below -7.5 bars. The gravimetric moisture levels that occurred in the fall averaged 20% and 29% at Komarno and Petersfield, respectively. Boyd (2003) produced a curve relating gravimetric soil moisture levels to osmotic potentials for a fine sandy loam and a clay textured soil. The fine sandy loam designation best represents the soil at Komarno, and the clay the soil at Petersfield. Using the relationships presented by Boyd (2003), the osmotic potential that existed in a fine sandy loam when soil gravimetric moisture was 20% was approximately -0.25 bars. Osmotic potential in a clay soil when soil gravimetric moisture is 29% is approximately -0.05 bars. Even at the low soil gravimetric moisture levels we measured in the fall of 2001, the osmotic potential of the soil may have still been within the range required for germination of false cleavers seed.

Soil temperature may have had a greater influence than soil moisture on the low levels of recruitment occurring in the fall of 2001. Benech-Arnold et al. (2000), suggested that in temperate environments where soil moisture is not limiting, temperature is the main factor impacting seed dormancy. We suspect that the false cleavers biotype we used in our experiment is a summer annual. As such, secondary dormancy can be induced by high temperatures that typically occur mid-summer. Thus, the higher temperatures occurring during the summer period may have been more influential on fall false cleaver recruitment than the lower temperatures in the fall.

4.3.3(iii) Volumetric Soil Moisture

Volumetric soil moisture was significantly different between the tilled and untilled treatments in only the over-wintering experiment at Komarno. In the spring 2002 experiment, soil volumetric moisture averaged over 0-6cm was not significantly different between tillage treatments at either site (Table 4-8). This was similar to the trend observed for soil gravimetric moisture levels in the spring of 2001 and 2002 (Table 4-2). At Petersfield, the soil volumetric moisture averaged over all tillage treatments was 44.84 (± 0.018) % and 46.56 (± 0.015) % for the spring 2002 and over-wintering experiment, respectively. At Komarno, mean soil volumetric moisture in the spring 2002 experiment averaged over all tillage treatments was 30.21 (±0.007)%. For the over-wintering experiment at Komarno, mean soil volumetric moisture was not significantly different between the two tilled treatments, T1 and T2. Soil volumetric moisture averaged for T1 and T2 treatments was 27.82 (± 0.010) %. Soil volumetric moisture was significantly different between the tilled treatments (T1 and T2) and the untilled treatment (T0) in the

over-wintering experiment at Komarno. The mean soil volumetric moisture for the untilled treatment was 31.72 (± 0.011) %. This difference in the volumetric soil moisture

Table 4-8. Mean soil volumetric moisture (%) measured at Petersfield and Komarno, MB in the spring 2002 and over-wintering experiments measured in the spring of 2002, as affected by tillage treatment; no additional tillage after the start of the experiment (T0), one fall tillage operation only (T1) and one spring tillage operation (T2) and depth; 0-2cm, 2-4cm and 4-6cm.

		Petersfield		Komarno	
Factor		Spring 2002	Over-wintering	Spring 2002	Over-wintering
Tillage					
	T0	44.93a[a]	47.65a	30.52a	31.76a
	T1	-	46.59a	-	27.34b
	T2[b]	44.75a	45.46a	29.51a	28.30b
LSD		0.039	0.038	0.016	0.021
Depth					
(cm)	0-2	33.58a[a]	38.29a	22.72a	21.45a
	2-4	47.70b	48.52b	31.93b	31.72b
	4-6	53.24c	52.88c	35.40c	34.23c
LSD		0.049	0.038	0.021	0.021

[a]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).
[b]For the over-wintering experiments, T2 would include two spring tillage operations; one in the spring of 2001 and another in the spring of 2002, and one fall tillage operation which was applied in the fall of 2001.

levels between tillage treatments in the over-wintering experiment at Komarno did not translate into distinct differences in recruitment between the tilled and untilled treatments, suggesting that moisture was not limiting recruitment in this experiment at this site.

4.3.3(iv) Influence of Depth on Soil Moisture

In the spring of 2002, soil volumetric moisture was measured at three depths; 0-2, 2-4, 4-6cm. At Komarno and Petersfield, mean soil volumetric moisture was significantly lower on the surface relative to increasing depth for the spring 2002 experiments and the over-wintering experiments (Table 4-8). As expected, the most extreme difference in soil moisture was seen when sampling the surface level to deeper depths. Because the soil surface is directly exposed to the air, the soil tends to dry out during periods without rainfall and become very wet or even saturated after precipitation. Soil at depth is not exposed to the same wetting and drying forces, and as such, tends to experience less extreme variation in moisture levels. This effect is similar to the effect of depth on soil temperature fluctuation. Extreme wetting and drying events that are typical of the soil surface can have various effects on seed germination. Seeds that are exposed to multiple wetting and drying periods could become non-viable, dormant, lose hydration-dependent steps toward radicle emergence through dehydration, or incrementally accumulate events required for radicle emergence (Allen et al. 1993). The response of seeds to wetting and drying events will depend on a number of factors and will be species specific. For example, seeds of two grass species, perennial ryegrass (*Lolium perenne* L.) and annual bluegrass (*Poa annua* L. var. annua), were able to germinate after being exposed to repeated hydration-dehydration episodes (Allen et al. 1993). Information on the response of false cleavers seed to microsite condition extremes is limited. Boyd and Van Acker (2003) showed that cleavers recruitment was reduced when soil moisture was allowed to fluctuate between field capacity and 1/6 field capacity.

This result suggests that moisture fluctuations may not be favorable for cleavers recruitment.

4.4 Summary and Implications

Low levels of recruitment were observed in the fall 2001 experiments at both sites. At Komarno, recruitment was significantly greater in the T1 and T2 treatments relative to the T0 treatment. No significant tillage effect was observed between the T2 and T1 treatments at Komarno. At Petersfield, there were no differences in recruitment observed between tillage treatments. Low recruitment may have been associated with abnormally low soil temperature and moisture conditions in the fall of 2001. However, it seems more probable that lower recruitment was a reflection of the summer annual growth habit of the false cleavers population used in our experiment.

Recruitment of false cleavers seed when sown in the spring tended to be greater in tilled versus untilled treatments. Our results show this in three of four site years. Others, have commonly attributed the variation in the recruitment response to tillage was thought to be associated with the direct changes to the soil physical conditions that resulted from the presence or absence of disturbance. This, however, does not appear to be the case in our experiment. Structural changes in soil environment as measured using bulk density were only significantly different between tillage treatments at Petersfield in the spring 2001 experiment. In the spring 2001 and spring 2002 experiments, soil gravimetric or volumetric (measured in 2002 only) moisture were not significantly different between tillage treatments at either site. In three of four spring site years, soil

temperature measured at 1cm (measured in 2002 only) and 4cm was shown to vary between tillage treatments. Though temperature is an important factor affecting germination and shoot elongation, the differences observed between tillage treatments in our experiments were very small and not likely great enough to drive the dramatic differences in recruitment between tillage treatments which we observed in the field. In our experiments, tillage did not appear to affect soil physical conditions in a biologically significant manner with respect to false cleavers seedling recruitment. The bead placement experiments showed that the majority of false cleavers seed would have likely been located on, or near, the soil surface in untilled treatments, and within 1-4cm of the soil surface in the tilled treatments. Measurements taken in the spring of 2002 captured the differences in soil conditions occurring with depth. Mean bulk density and volumetric soil moisture measurements during the same period tended to increase with depth in the soil. Mean daily maximum soil temperature was greater on the soil surface and mean daily minimum soil temperature was lower on the soil surface versus deeper soil depths. The magnitude of difference occurring with depth was greater for the mean daily maximum soil temperature relative to the mean daily minimum soil temperature. The combined effects of maximum and minimum temperatures resulted in an overall mean soil temperature that tended to decrease with increasing soil depth. Unlike the differences in temperature that occurred between tillage treatments, the differences that occurred with soil depth were considerable. Mean soil temperatures recorded at 1cm were on average 0.83°C higher than those recorded at 4cm when averaged over both sites in 2002. This difference equates to a difference of 60 GDD between soil depths, when a 75 day emergence period is considered. Using wild oat emergence as a measure, this

difference would equate to a difference in emergence of 18%. This is considerable if we recall that the temperature differences between tillage treatments led to an estimated wild oat emergence difference of only 7%. Thus, the conditions occurring within the soil profile vary significantly with depth, and these differences can affect the rate and extent of seedling recruitment. Our results suggest that differences in vertical weed seed location associated with differences in the tillage intensity, and the resulting differences in microsite conditions experienced by seeds at different depths within the soil profile, led to the differences in spring false cleaver recruitment between tillage treatments. False cleavers seeds were exposed to different conditions in tilled versus untilled treatments, however, the differences were not driven by direct changes in soil properties, rather, they were associated with the impact of tillage on seed placement and the differences in microsite conditions among soil depths, especially light exposure. Using this premise, we might expect that fields that remain untilled after seed rain would have lower recruitment relative to fields that are tilled to a moderate depth. Over time, one would expect that surface placed seeds in the untilled fields would either be covered by decomposing stubble or moved below the surface via soil cracks. Thus, the lower recruitment levels in these fields may be short lived, depending on the duration of the light induced secondary dormancy and the longevity of the seed.

CHAPTER 5

General Discussion

5.1 The Importance of Information on the Biology of Weed Species

In the past, weed science research focused largely on increasing our understanding of how weeds grow. This research led to an accumulation of knowledge on the conditions necessary for the establishment and growth of a given weed species. Since then, weed science studies have moved away from studying weed biology and have turned to investigations focusing on chemical weed control. Herbicides have become an integral component of most farming operations, and in general, they have proven to be effective in reducing weed pressures within a given cropping season. However, they have not come without costs. As a result of our dependence on a single means of weed control, we have caused weed populations to evolve herbicide resistant biotypes, and thus, reduced the efficacy of the products that we so wholly depend on. In realizing the limitations of an agricultural system based solely on chemical weed control, producers and scientists have recognized a need for alternative methods of weed control. In response to this, there has been a resurgence of studies investigating weed biological processes. The value of weed biology information rests in our ability to use that knowledge to adapt management practices to limit the success of weeds in a given agricultural system. In the case of our study, this involved altering the form and intensity of tillage to try and capture weaknesses in false cleavers recruitment associated with a sensitivity to seeding depth. However, changes in management practices are not restricted to changes in the tillage regime. Altering crop seeding rate, seeding date,

fertilizer placement or crop rotation are examples of crop management practices that may be altered to reduce the success of a given weed species in a particular context.

Knowledge of weed biology also has broader applications. Understanding the conditions required for the establishment of a weed species is important in predicting the movement of a given weed species at various scales. Weed surveys have shown a change in the range of cleavers infestations within Manitoba over the past 30 years. Surveys are used to track the movement of cleavers into new areas, and also to identify areas where cleavers remain consistently absent. The absence of cleavers establishment in certain areas may be due to the lack of seed introduction. However, environmental restrictions for establishment may also be contributing to the absence of cleavers in certain regions within Manitoba. Cleavers appear to be less prevalent in regions with higher July average daily temperatures, for example, cleavers are absent in the Winkler and Emerson ecodistricts where the average daily temperature in July is 20.0°C or higher. This may relate to limitations imposed on cleavers recruitment by high temperatures. Thus, developing a more detailed understanding of the conditions under which cleavers can establish may facilitate predictions of areas within a region which may be susceptible to invasion.

5.2 The Value of Indoor Experiments Versus Field Experiments

Successful seedling recruitment is dependant on the proper combination of a number of environmental conditions. The specific requirements for recruitment can vary broadly between species. Unfortunately, seed biology is not well studied for most weed species. This is true for false cleavers. Little information is available on the conditions

necessary for breaking dormancy, germination and emergence. Available information has generally been obtained through controlled indoor experiments. Such experiments tend to focus only on the germination component of recruitment and generally consider the influence of only one environmental factor at a time. In an attempt to better represent the realities of field conditions, some researchers have included more than one environmental variable in their seed germination studies at one time and have tried to investigate the interactive effects of these factors. Understanding the effect of these interactions on seed germination is important. The complexity of interactions occurring under field conditions would be difficult to replicate indoors. Indoor experiments are appealing to researchers because they are relatively easy to conduct and they often produce clear results. For example, Sjostedt (1959) conducted simple germination studies on *G. aparine* and found the optimum temperature for germination to be 12-15°C. Though controlled indoor experiments are useful in identifying the germination response of seeds to certain environmental variables, the resulting information may not be effective in predicting recruitment under more complex field conditions. As a result, relationships identified indoors should be validated under field conditions. In our study, for example, cleavers sensitivity to seeding depth and light exposure previously identified in controlled studies (Boyd and Van Acker 2003; Malik and Vanden Born 1987c), and was tested in the field using tillage to induce variation in seed depth and duration of light exposure. Studies, such as ours, require the measurement of microsite conditions, including, soil moisture and soil temperature, in conjunction with seedling recruitment. However, measuring soil conditions in the field is difficult, especially at a scale that is representative of a microsite.

5.3 Difficulties Associated with Measuring Microsite Conditions in Soil

Two main difficulties encountered in measuring microsite conditions are; identifying the measurement scale that is appropriate for the microsite of interest and determining a method to capture environmental variation at that scale. According to the definition of a microsite, the conditions that are of interest are occurring within the area directly surrounding a seed. This area could be extremely small. For example, in the case of the false cleavers seeds used in our experiment, the seed diameter was approximately 1.5mm, resulting in a seed volume of only $1.77mm^3$. The microsite that is influential for a seed of that size may be only slightly larger than the actual size of the seed. Measurement of conditions at such a fine scale is not possible using current technologies. In fact, the absence of capable technologies is a major hindrance to capturing environmental variation within microsites. There are no devices available to continuously measure changes in environmental conditions occurring within a small volume of soil. This is especially true for soil moisture, which is commonly measured by removing a sample of at least $20cm^2$ (2cm x 2cm x 5cm). Soil moisture measures obtained using samples of this size represent the average conditions occurring within multiple microsites. If, for instance, recruitment was only successful in a certain region of the 0-5cm sampling zone, the soil moisture estimate obtained may not be representative of the actual conditions stimulating the recruitment event. In our experiment, where weed seed placement and microsite conditions were found to vary with depth, the measurement scale used proved to be very important. When soil moisture sampling was done to a depth of 5cm, we were not able to capture important differences

in soil conditions. However, when sampling was done at a finer scale; from 0-2cm, 2-4cm, and 4-6cm depth, differences in soil moisture conditions were revealed. This information, in combination with data on seed placement, contributed to an understanding of the conditions leading to recruitment differences observed in the field.

Though sampling within a smaller region of the soil profile may provide information that is more representative of microsite conditions, it can also result in highly variable data. This is largely due to the heterogeneous nature of soil. The composition of the soil can vary extensively both horizontally and vertically. These differences are associated with a number of factors, including, the textural composition, elevation and organic matter content of the soil. Measurement error associated with soil heterogeneity can be reduced by increasing sampling size. However, this is not always practical. For example, in our experiment the number of temperature sampling points was limited by the number of sampling devises available. Fortunately, there are other methods that can be used to reduce sampling error. In our study, reducing error associated with horizontal variation in soil conditions was partially accomplished by using an experimental design (blocking) that accounted for differences in soil conditions within a field. Variability was further reduced by sampling discriminately from only between the crop row and by avoiding obvious high and low areas.

Vertical variability in soil microclimatic conditions tend to be more predictable than horizontal variability in these same conditions. For example, organic matter levels are generally greater near the surface where plant material is deposited than at deeper depths. In our experiment, where seed placement varied, we were interested in measuring differences in soil microclimate conditions vertically within the soil profile.

Measuring to capture small differences in soil conditions over relatively fine depth increments can be difficult. In the case of soil volumetric moisture sampling, it was imperative that measures be taken at consistent depths, and post-sampling moisture loss avoided. This required considerable care when sampling and the immediate placement of the soil samples into tightly sealed containers. However, even using careful sampling practices, errors can still occur. For example, samples may contain rocks or plant material that would generate an inaccurate measure. In our study, errors in soil temperature measurement were avoided by ensuring the accurate initial placement of sampling devices and by reinforcing the devices that were positioned near the soil surface to prevent movement and resurfacing.

In addition to spatial variability, microsite measurements are further complicated by temporal variability of soil conditions. The soil environment changes within a number of time scales including; minutes, hours, days, months, seasons and years. Identifying the temporal scale that is of importance for recruitment can be difficult, as this may vary depending on the biological process being considered. For example, monthly averages may be sufficient to capture the conditions affecting changes in the level of seed dormancy occurring within a year, yet this measurement would be insufficient to capture the changes affecting seed germination and emergence, for which daily averages may be more appropriate. Difficulties arise in measuring changes in the soil microclimate at different time scales based on the availability of appropriate measurement devices. In the case of soil temperature, continuous measurement over time is possible. This allows us to record temperature changes over very small time periods, including changes occurring within 15 minute intervals. Measuring soil moisture changes that occur over time is

possible using a measurement probe. However, probes tend to measure at a spatial scale that is too coarse to capture changes in the soil microclimate. As a result, changes in soil moisture conditions cannot be recorded continuously within a spatial scale that is appropriate for microclimate measures. Discontinuous sampling means that important changes in soil moisture conditions may be missed if they occur in between sampling periods. The value of information captured within a fine temporal scale will vary depending on the sensitivity of a particular weed species to short duration changes in soil temperature and/or moisture conditions.

5.4 Practical Implications and Future Studies

The absence of basic information on the biology of North American populations of false cleavers has hindered our ability to understand the dynamics of this weed species in agricultural systems. Researchers have investigated certain aspects of false cleavers biology including the impact of light, seeding depth and oxygen on germination or recruitment. However, further studies are required to narrow information gaps, specifically in the areas of seed biology and recruitment dynamics. Very little is known about the dormancy behavior and seed longevity of false cleavers. This information is essential to understanding the long term dynamics of this species, and determining more effective means of control of this weed. For example, if seed longevity is short, then deep tillage may be effective in reducing the false cleavers seedbank, however, if seed longevity is long than perhaps shallow tillage, which facilitates seedling recruitment, may reduce seedbank levels.

Studies in the area of seed predation and decomposition will also help to more completely understand false cleavers recruitment dynamics. In our over-wintering experiment, false cleavers recruitment appeared to be restricted in the spring. This may have been associated with high dormancy levels or reduced seed viability, however, seed predation and decomposition may have also been important factors. Studies investigating seed predation of other weed species have shown that predation levels can be high. Others indicated that cleavers seed remains viable after passing through the gut of predators. This may prove to be important to false cleavers seed spread, if predation levels are high and predator movement broad

One of the limitations in our study was the short duration of the spring recruitment period observed. We chose the duration of our weed seedling recruitment period based on the approximate start of weed emergence in the spring and the standard timing of in-crop herbicide application. In doing so, we maintained a more realistic farm scenario. This resulted in a recruitment period of between 3 and 4 weeks. Within this period maximum recruitment levels were not necessarily reached. As such, in this study we recorded differences in the rate of false cleavers recruitment between tillage treatments, however, we did not necessarily capture the actual differences in the maximum recruitment between tillage treatments. In observing recruitment for a longer period in the spring we may have found that the differences in the level of recruitment occurring in untilled and tilled treatments may have been reduced. Unfortunately, tracking recruitment to maximum levels with such large weed populations is complicated. It is difficult to identify individual false cleavers seedlings and track previously counted seedlings as populations grow. One way to remedy this is to remove seedlings after

counting, however, that may stimulate further recruitment. Though the intention of our study was to follow false cleavers dynamics using management practices that reflected reality, it would have been interesting to try and record differences in the maximum recruitment levels between tillage treatments to account for possible differences in the rate of recruitment.

It would also be useful to investigate false cleavers dynamics over multiple seasons. Recruitment differences occurring under different management practices, such as varying the tillage intensity, may change over time. This was evident by the inconsistencies observed in recruitment between tillage treatments in the over-wintering experiment versus the spring 2001 and spring 2002 experiments. In assessing the impacts of tillage on false cleavers recruitment, long term studies may better capture recruitment differences resulting from changes that develop over time, for example, the accumulation of crop residues on the soil surface. As a result, long term studies would provide a more complete picture of false cleavers recruitment dynamics as affected by tillage intensity. In a longterm study we would be better able to assess if, in fact, false cleavers recruitment is reduced in long term no-till fields relative to long term conventionally tilled fields. This information would be important to producers.

It would also be interesting to study the species make-up of cleavers on the Canadian prairies. Little is known of the actual ratio of *Galium aparine* to *Galium spurium* in Canada, and if one species is more predominant in agriculture areas versus natural areas. In the past, it has been assumed that only *Galium aparine* was present in agricultural fields. This was based on the identification of species using morphological criteria, which is not a reliable method. However, more recently researchers have begun

to suspect that *Galium spurium* may be the predominant species is agricultural areas. In knowing which of the two species is present in agricultural fields, or if both species are weedy, we would know whether to focus our studies on a single weedy species or both. Investigating the potential fitness differences between the two cleavers species would also be interesting. Differences in fitness might provide evidence to support the results of a species survey, if a single species is found to be predominant in agricultural fields and that same species proves to be more fit. If both species are present in agricultural areas, investigating differences in the response of the two separate species to control methods, including herbicide control, would be important in understanding how best to limit future infestations. If, for instance, differences between the two species enable them to take advantage of different niches within agro-ecosystems, cleavers may pose an even greater invasion and competition threat in agricultural areas.

CONCLUSIONS

Based on experiments conducted during the 2001 and 2002 cropping seasons, spring false cleavers recruitment was greater where the soil was tilled relative to where it was not. This result suggests that false cleavers recruitment may be reduced in untilled fields versus tilled fields. Thus, reduced tillage may lead to less false cleavers recruitment and curtail the population growth of this species in certain fields and regions.

Measurements of recruitment microsite conditions indicate that recruitment differences were associated with changes in the conditions experienced by seeds resulting from tillage induced differences in the position of false cleavers seed within the soil profile. Results obtained in the field seem to reinforce the relationship of false cleavers recruitment to seed depth and light exposure that was identified during controlled indoor experiments. As a result, our experiment was effective in field-validating these aspects of false cleaver biology.

Fall recruitment recorded in 2001 was very low, suggesting that the false cleavers population used in our study was a summer annual.

Although the results of this study were relatively conclusive, the experiments were conducted in the short term and represent only a single recruitment period. Longer population dynamic studies would provide further verification of the results we obtained from our short term study, and a more comprehensive understanding of the influence of tillage on false cleavers management. In our study, we also found that it was difficult to adequately characterize microsite conditions in situ, and efforts need to be made to create devices and methods to enable this form of measurement.

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APPENDIX A

Description and Timing of Field Procedures from May 2001 to June 2002

Table 1. Description of Field Procedures and Sampling Scheme For Petersfield and Komarno, MB from May, 2001 to June, 2002

Date	Action	Relevant Experiment
May 30, 2001 (Petersfield) June 5, 2001 (Komarno)	▪ Cleavers seed sown on the soil surface ▪ T2 plots are cultivated	
June 25, 2001	▪ Cleavers emergence counts	Spring Experiment
September 6, 2001	▪ T1 and T2 plots are cultivated at both Petersfield and Komarno sites.	
October 8, 2001	▪ Cleavers emergence is recorded at both Petersfield and Komarno.	Fall Experiment
October 11, 2001	▪ Cleavers seed is added to selected treatment plots at both Petersfield and Komarno. ▪ Newly seeded T1 and T2 treatment plots are cultivated at both Petersfield and Komarno.	
May 28, 2002	▪ New trial plots are established at both Petersfield and Komarno. ▪ Cleavers seed is sown on newly established trials. ▪ T2 plots are cultivated on newly established trials and on those established in 2001.	
June 27, 2002	▪ False cleavers emergence counts are done on trials established in 2001.	Over-wintering Experiment
June 27, 2002	▪ False cleavers emergence counts are done on the trials established in 2002	Spring Experiment

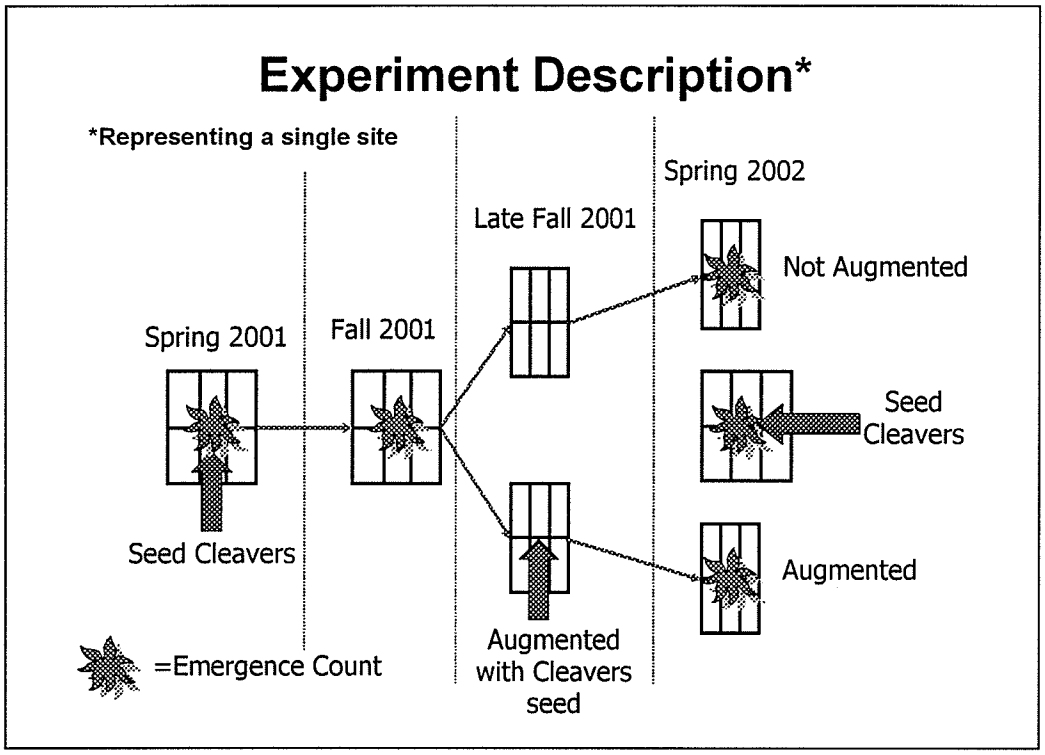

Figure 1. Diagram of the timing of false cleavers seed spread and emergence counts.

APPENDIX B

Results of the Flow Cytometry Preformed on the Seedlot Used in Our Experiment

Table 1. Mean DNA content within plant cells for three control populations of cleavers and one test population, obtained using flow cytometry. The values presented represent the amount of DNA present in the cells of the sample relative to a standard diploid specimen.

	G. spurium (Control)[a]	*G. aparine* (Control)	*G. aparine* (Control)	Unknown (Test)[b]
Plant Replicate				
1	68	167	171	72
2	72	165	169	74
3	69	171	178	71
4	71	161	170	73
5	67	155	169	73
6	-	-	-	73
7	-	-	-	73
8	-	-	-	73
9	-	-	-	72
10	-	-	-	73
Mean	69	164	172	73
Index[c]	1.00	2.38	2.49	1.06

[a]Control samples obtained from Herbiseed, Twyford, England.
[b]Test sample obtained from Brett-Young Seeds Ltd. Winnipeg, MB.
[c]Index values are calculated using the mean value of *G.spurium* equal to 1.00.

APPENDIX C

Results of the Simulated Seasonal Transition Seed Germination Experiment

Table 1. False cleavers germination (%) on petri plates for three runs (1,2,3) occurring after either a cool-dry pretreatment and warm-moist conditions (Warm), or a warm-dry pretreatment and cool-moist conditions (Cool), wetted with either KNO_3 or distilled H_2O.

	KNO_3			H_2O		
Factor	Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Moist Temperature						
Warm	63.40a[a]	61.33a	80.33a	34.44a	5.33a	4.23a
Cool	74.90b	91.00b	92.00b	71.78b	71.10b	74.67b
LSD	6.488	8.123	6.389	9.521	4.271	6.937

[a]Means within a column followed by the same letter are not significantly different according to the Fisher Protected LSD test ($\alpha = 0.05$).

APPENDIX D

Air Temperature and Accumulated Precipitation Relative to Long Term Averages

Table 1. Average maximum (max), average minimum (min) and mean air temperature (°C) and accumulated precipitation (mm) at two sites, Komarno and Petersfield, over three measurement periods; June 7, 2001 to July 5, 2001 (spring 2001), June 2, 2002 to June 30, 2002 (spring 2002) and September 6, 2001 to October 8, 2001 (fall 2001). Temperature (°C) and precipitation (mm) long term averages are also presented.

	Petersfield			Komarno		
	Spring 2001	Spring 2002	Fall 2001[a]	Spring 2001	Spring 2002	Fall 2001[b]
Air Temperature (°C)						
Max	24.1	25.0	17.7	23.5	24.6	17.6
Min	9.8	11.3	3.6	10.2	11.5	4.1
Mean	18.0	18.2	10.6	18.0	18.2	10.6
AirTemperature Long Term Average (°C)[c]	17.3	17.3	12.4	17.3	17.3	12.4
Accumulated Precipitation (mm)	103.6	86.0	17.6	76.2	109.4	19.6
Precipitation Averages (mm)[c]	93.0	93.0	53.8	93.0	93.0	53.8

[a]Data obtained from the Petersfield weather station (SW1-16-3E) owned and operated by the Agrometeorological Centre of Excellence, Carmen, MB.
[b]Data obtained from the Teulon weather station (SW23-16-2E) owned and operated by the Agrometeorological Centre of Excellence, Carmen, MB.
[c]Data based on 29 year averages for the Selkirk weather station owned and operated by Environment Canada.