Fall rye cover crops increase sustainability of dry bean production

BY

HEATHER FLOOD

A Thesis
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For the Degree of

MASTER OF SCIENCE

Department of Plant Science
University of Manitoba
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

Of

MASTER OF SCIENCE

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ABSTRACT

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Fall rye, in addition to being able to suppress weeds by physical factors attributed to rye's biomass, is recognized as a plant with allelopathic properties. Research on weed control benefits of fall rye cover crops has been conducted in several Canadian provinces. The objective of the present study was to examine effects of fall rye cover crops on weed density and growth and yield of dry bean (*Phaseolus vulgaris* L.) crops in Manitoba. Field experiments were conducted over four site-years in southern Manitoba in 2006 and 2007. Two rye termination times were used: Soil incorporation when rye produced low or high levels of biomass, varying across all four site years. Rye treatments, in the absence of in-crop herbicides, resulted in 44% to 72% significantly fewer broadleaved weeds and 43% to 88% fewer grass weeds at time of full bean soil emergence. Additionally, rye reduced total accumulated weed biomass in the dry bean crop such that when in-crop herbicides were absent, rye reduced total weed biomass compared to the control treatment by 52% to 92%. Soil incorporation when rye produced greater biomass did not result in fewer weeds compared to incorporation when rye produced less biomass, which may indicate that weed suppression by rye was less due to physical suppression and more due to competition and chemical suppression. Dry bean yields following rye were found to increase in one site-year, decrease in another site-year and were similar to controls in two site-years. Results from this study indicate that cover crop water usage in spring, combined with environmental and soil conditions were responsible for the observed decrease in yield. A second finding in field studies was bean yields increased when time of initial soil tillage was seven to ten days prior to seeding compared to beans seeded immediately after soil tillage. This may indicate that farmers who begin seedbed preparation at least a week in advance of seeding will improve productivity of the crop. In addition to field experiments, preliminary investigations to determine the allelopathic effects of greenhouse and field grown fall rye tissues on redroot pigweed, green foxtail and dry bean seeds, showed that rye extracts significantly inhibited germination in the two weed species, yet, had no effect on dry bean seed germination. This result provided

further evidence to support the utility of cover crops in dry bean production. A second experiment with aqueous extracts from field grown tissues of three winter cereal cover crops, fall rye, winter wheat and winter triticale, were tested on redroot pigweed, green foxtail and dry beans to determine their relative allelopathic effects on seed germination. All three cereal extracts were found to have similar inhibitory effects on redroot pigweed germination compared to water only controls. Likewise, all extracts inhibited germination in green foxtail compared to controls, however, winter triticale was the most suppressive to this species among the three. Dry bean seed germination was reduced 66% by winter wheat extracts and 24% by winter triticale extracts, whereas fall rye extracts produced the same germination response in beans as water controls. These results suggest that, unlike fall rye, winter wheat and winter triticale are allelopathic to dry beans and may not be suitable cover crops to use in dry bean production systems.

1.0 INTRODUCTION

Many studies have identified the benefits of including rye in rotation as a winter cover crop, resulting in reduced weed population densities and biomass due to rye's high biomass production and potent toxicity to weeds (Einhellig and Leather, 1988). Barnes and Putnam (1983), who observed total weed biomass reductions of up to 90% compared with unplanted controls for lambsquarters *(Chenopodium album),* redroot pigweed *(Amaranthus retroflexus)* and barnyard grass *(Echinochloa crusgalli)* in a no till pea system devoid of in-crop herbicides suggested that rye has allelopathic properties. Combining rye allelochemicals with moderate herbicide applications has been found to achieve greater weed control compared to systems of either rye or herbicides as the exclusive method of weed control (Einhellig and Leather, 1988). Although higher residue rates leading to greater surface cover may contribute to herbicide interception, Crutchfield et al. (1986) determined that increased weed control was attained by increasing levels of allelopathic wheat straw despite herbicide interception. Thus, adoption of a system using a combined form of weed control can be successful and have environmental benefits.

Weeds will always be a concern in crop production. High costs of herbicides and resistant weeds are a concern for farmers. Herbicides in the environment are a concern for many. Although we require herbicides for much of our production, these concerns have led us to search for other methods of weed control provided through natural plant on plant interactions.

The ability of certain plants to control their surroundings by suppressing the germination and growth of other plants has long been realized by farmers and scientists. However, the way by which these plants establish this control is less well understood. In addition to physical weed suppression by rye's biomass, rye has been documented as a plant with phytotoxic properties (Einhellig and Leather, 1988), therefore, rye's use may encourage weed suppression, with less need for herbicides.

Although fall rye cover crops are known to control weeds (Price et al., 2006), little research has been conducted in Canada. Comprehensive studies of how Canadian rye cultivars affect weed suppression, therefore, are necessary.

In addition, rye's ability to germinate and grow quickly and its winter hardiness make it easily adoptable as a winter cover crop throughout the colder areas and climates of the prairies. Rye's quick establishment in the fall and rapid resumption of growth in the spring make this cover crop ideal for reducing wind and water soil erosion. Its far-reaching, deep root structure (Bowman et al., 1998) allows it access to soil water found at increasing depths. Although much research has been dedicated to soil moisture conservation by rye residues left on the surface, little literature can be found on rye's ability to access and intercept moisture during its growth period and on how this trait can be effectively utilized. Rye cover crops and the soil moisture deficits they generated in a in a subsequent corn crop had a hindering effect on yield as a result of dry soil conditions and corn's sensitivity to drought (Kamprath et al., 1968). In Manitoba, dry beans often suffer from flooding or excess moisture conditions in early spring and summer. Hence, water usage by cover crops may be an answer to growers who face such constraints.

Distinguishing competition from chemical interference—allelopathy—is difficult under field conditions. Therefore, bioassays using aqueous extracts of fall rye are used to investigate the possibility that allelochemicals produced by rye are in part responsible for inhibiting germination in target weed species.

In field experiments, the dominant broadleaved specie suppressed by rye cover crops was redroot pigweed and a dominant grass weed was green foxtail. Therefore, these species were chosen for the bioassays. Dry beans grown following rye cover crops in field experiments sometimes exhibited poor establishment, development and yield; therefore, it is important to determine if aqueous extracts from rye have any deleterious effects on the non targeted bean seeds.

In addition to fall rye; winter wheat and winter triticale may be used as cover crops. As with fall rye, winter wheat is known for possessing allelopathic properties (Perez, 1990; Kruse et al, 2000) and it may be suggested that winter triticale, the hybrid of rye and wheat, also holds allelopathic potential.

The principle investigations of this study are:

(1) **Hypothesis**: Fall rye will inhibit weed emergence in a growing bean crop.
Objective: Determine how a fall rye cover crop affects weed populations in the presence and absence of post-emergent herbicides.

(2) **Hypothesis:** More rye biomass equals more weed suppression.
Objective: To determine if higher incorporation rates of a fall rye cover crop will lead to greater weed suppression and what rate optimizes weed suppression without inhibiting dry bean productivity.

(3) **Hypothesis:** Rye cover crops can dewater wet soils creating more favorable establishment conditions for dry beans.
Objective: To determine the effects of the rye cover crop on spring soil moisture conditions.

(4) **Hypothesis:** Allelopathy is one of the mechanisms responsible for rye's suppressive effects on other plants
Objective: To determine the phytotoxic effects of fall rye extracts on weeds and beans.

(5) **Hypothesis:** Allelopathy exists in several related cover crop species.
Objective: To compare the phytotoxic effects of winter triticale and winter wheat to those of fall rye.

2.0 LITERATURE REVIEW

2.1 Common dry bean

2.1.1 Origin and distribution

Common bean (*Phaseolus vulgaris* L.), known as dry bean in western North America, is an ancient crop thought to date back more that 8,000 years to a wild ancestor, *Phaseolus aborigineus*, which was first described in South and Central America (Gentry, 1969; SPG, 2000). Globally, the term dry bean refers to several classes of beans including white pea—navy bean—, pinto, black, dark and light red kidney, cranberry, small red, Great Northern, pink, brown and white kidney (AAFC, 2005). Since its discovery, the common bean has been grown on all continents, except Antarctica (Gepts, 1998) with the majority of its distribution occurring in the Americas, east Africa, east Asia and west and southeastern Europe (SPG, 2000).

2.1.2 Bean biology and ecology

Beans, *Phaseolus vulgaris*, are of their own section in the genus *Phaseolus*, belonging to the Leguminosae family and subfamily Papilionoideae (Miklas and Singh, 2007). Among all bean cultivars, there is a great deal of variation in growth habit, from the determinate bush type to the indeterminate climbing types. Singh (1982) propsed a system that allowed all bean varieties to be classified, based on certain growth habits, into one of four types. The basis for this classification system depended on terminal bud (vegetative vs. reproductive), stem strength (weak vs. strong), climbing ability (nonclimber vs. strong climber) and fruiting pattern (basal vs. along entire or partial stem length) (Miklas and Singh, 2007). As a result, these types are the Type I = determinate upright bush, Type II = indeterminate upright bush, Type III = indeterminate, prostrate, nonclimbing or semi-climbing and Type IV = indeterminate, strong climbers. Determinate growth type bean plants stop producing new leaves once flowers have developed, whereas indeterminate type plants continue to grow, flower and pod as long as conditions remain favorable (MAFRI, 2006). The white pea bean, or navy bean, may

be either of Type I or Type II in solid seeded systems, or Type III or IV in row crop production systems.

The cotyledons of dry beans do not remain below ground following germination. Once initiated, the cotyledons push up through the soil and are exposed (SPG, 2000), causing the new plants to be prone to frost damage. The radicle or embryonic root also forms at this time and later develops into a fibrous type root system marked with a main root or tap root (Miklas and Singh, 2007). Generally, bean root systems will bear nitrogen-fixing nodules beginning a few weeks following emergence until the end of flowering. Dry beans are typically capable of fixing 25% to 50% of their nitrogen needs (SPG, 2000). The first leaves that form on young bean plants are oppositely arranged and single, or unifoliate, however, all succeeding leaves will grow in an alternate arranged phyllotaxy in clusters of three leaflets, or trifoliates (Gentry, 1969 SPG, 2000). Early bean developmental stages are determined based on the number of completely formed trifoliates (MAFRI, 2007a). Bean plants, on average, will produce a new leaf every four to six days, until, triggered by day-length and temperature change, flowering will begin (Miklas and Singh, 2007). Indeterminate growth types will usually produce vines just prior to flowering (SPG, 2000). Flowering lasts approximately two weeks, and each flower is capable of producing a single pod. Flowers can be pink, purple, white or bicolor and typically self-pollinate (SPG, 2000). Following flowering, pod production and seed set ensues. Mature pods are straight or slightly curved with considerable variation in size, shape and color (Miklas and Singh, 2007). Under ideal environmental conditions, individual pods can produce up to eight seeds (SPG, 2000). Extreme heat (i.e., over 32°C), however, can reduce growth, flowering and pod development (Singh, 1995).

Common bean is a short-day crop (White and Laing, 1989) and requires moderately cool environmental conditions with air temperatures between 18-30°C and has optimal growth temperature of 24°C (MAFRI, 2006). Ideal soil temperatures for germination should be above 12°C at planting (SPG, 2000). Therefore, when conditions are such that temperatures are ideal with 12 hour day-lengths, the common bean is able to germinate and reach maturity in 90-120 days (Miklas and Singh, 2007; MAFRI, 2006).

Dry beans can be grown in most soils, however, they are best suited to light to medium textured (loamy) soils, good moisture holding capacity and good drainage and

aeration (Park, 1985). Beans are sensitive to soil compaction and poor soil drainage as oxygen deficiency inhibits germination and growth (Park, 1985). Saline soils or soils with pH greater than 7.5 can be deleterious to common bean (Greenway and Munns, 1980) and, therefore, are unsuitable for bean production.

Beans are very susceptible to excessive moisture or saturated seedbed conditions. Cold, wet soils may result in poor germination and establishment of dry bean which can ultimately reduce final yield (Wuebker et al, 2001). Soybeans, among other bean species, are highly sensitive to cold temperatures and excess moisture during the first 6-24 hours after planting (Hatfield and Egli, 1974), which can result in poor germination and poor plant stands. Common bean is much less tolerant to these conditions than soybean (Cavers and Heard, 2001). Although beans cannot tolerate flooding (SPG, 2000), they respond well to continuous soil moisture throughout their growth period.

2.1.3 Global production

The majority of dry bean production occurs in North and South America. World dry bean production has increased from 15.7 Mt in 1995 up to 17.3 Mt in 2005 (AAFC, 2005). Canada produces about 1% of the world's dry beans; however, in 2003-2004 it became the world's third largest exporter of dry beans, accounting for approximately 11% of world exports (AAFC, 2006). Canadian dry bean production has also been on an upward rise over the past decade, with Ontario being the largest producer and accounting for 41% of Canadian production, Manitoba accounting for 37%, Alberta for 14%, Quebec for 4% and Saskatchewan for 3% (AAFC, 2006). The white pea, navy bean, accounts for the majority of dry bean acreage seeded (AAFC, 2006). In the 2004-2005 growing season, however, Canadian dry bean production dropped by 38% (AAFC, 2005). The decrease was due to poor growing conditions in Manitoba; mainly cool weather and excess moisture that began in spring and extended well into the growing season.

2.1.4. Bean production in Manitoba

The majority of Manitoba dry bean acreage is located in the Pembina Valley Region (MAFRI, 2007b). In the past, row crop production systems were the common practice for growing beans in Manitoba. However, due to the introduction of new bean

varieties and seeding and harvest equipment that can be easily modified, more producers are now able to grow beans by using a solid-seeded production system (MAFRI, 2006).

In row crop production systems, beans are grown in rows set 75 to 90 cm apart. Beans are seeded using either a row crop planter or a specialized bean planter (MAFRI, 2006). One drawback of the row crop system is there is increased competition within the crop row for water, nutrients and light as individual bean plants are much closer to one another compared to a solid seeded system. Under this production system, recommended navy bean seeding rates for row crop production are 45-55 kg/ha (MAFRI, 2006), much less than seeding rates required in solid seeded systems. Weed control in row crop systems usually combines inter-row cultivation, at least twice in a season, with a post-emergent in-crop herbicide applied as a band over the bean rows (SPG, 2000). In addition to weed management, inter-row cultivation makes it possible to aerate the root zone and to hill the bean plants which can reduce the incidence of diseases as well as allow for use of drop nozzles for fungicide applications (MAFRI, 2006). At harvest, bean grown in rows are pulled, windrowed and combined using a pickup header (MAFRI, 2006). Since beans can be pulled up in row crop production systems, pod height above the ground in less important compared to solid seeded systems where bean varieties must be upright and pods high above the soil surface to prevent harvest losses.

Producers currently growing cereals, flax and canola are now able to successfully grow dry beans with relatively minor modifications to existing equipment provided a solid seeded, or narrow row production system is employed. Under this system, beans are seeded with 12.5 to 20 cm row spacing (MAFRI, 2006). A benefit of this type of bean production system is there is limited competition within the crop for water, nutrients and light as individual plants are spread out more uniformly in the field (MAFRI, 2006). Recommended seeding rates for solid seeded systems are 90 kg/ha to 112 kg/ha (SPG, 2000), therefore, there is a higher seeding cost associated with this type of system compared to a row crop system for dry bean. One benefit associated with solid seeded systems compared to row cropping is the bean crop is more competitive with weeds due to the higher seeding rate which results in a higher plant population with greater field dispersal. Typically, weed control is achieved by applying in-crop herbicides, as cultivation is not possible under this system. However, there are a limited number of

herbicides registered for dry beans (MAFRI, 2006) and, therefore, weed management can be one of the greatest challenges using this type of bean production system. In addition, disease incidence tends to be higher using solid seeded systems since cultivation can not be used to aerate the soil and allow for increased air flow. At harvest, solid seeded beans can be either swathed or direct combined, provided that an upright variety has been grown and pods are high enough above the ground that the cutter bar can easily be positioned underneath (SPG, 2000). If pods are too close to the ground, harvest losses due to shattering or pod damage can be quite high under a solid seeded system.

Regardless of production system, bean production is well suited to The Pembina Valley of Manitoba in terms of length of growing season, temperature, moisture and soil type (Parks, 1985).

2.1.5. Challenges in Manitoba dry bean production

2.1.5.1 Soil erosion

Strong, winds in both fall and early spring are common place across the prairies and throughout Manitoba (Padbury et al., 2002). Typically the month of May, when most fields are still bare, is one of the windiest months in Manitoba. Wind speeds during this month of 30 km/hr gusting to greater than 70 km/hr are not uncommon in many areas of Manitoba (Environment Canada, 2008). A serious consequence of prevailing winds is soil erosion, whereby the nutrient rich topsoil is detached, transported and redeposited by the wind (Cruse et al, 2001). Loss of topsoil hinders a soil's ability to produce crops. The main factors affecting the degree to which wind erosion occurs are soil type, with loose, light textured sandy soils or broken down clay soils being most erodable, lack of vegetative cover—living crop, standing stubble or crop residues— and repeated freeze-thaw cycles that break down soil roughness (Kolk,2005). Since the prairies are characterized by long, cold winters, followed by short, hot summers, (Padbury et al., 2002) repeated freeze-thaw cycles are inherent.

Common bean is best adapted to light textured soils—erosion prone soils—as well as their requirement for late planting leaves the soils exposed for the better part of the spring. Common bean does not produce a lot of crop residue (Kolk, 2005), therefore,

there is little vegetative cover to protect the soil in the fall. Current planting methods for dry bean often rely on burying previous crop residues (Kolk, 2005). This combination can lead to soil erosion.

2.1.5.2 Excess spring moisture

The climate of Manitoba and much of the Great Northern Plains can be characterized as continental, with long, cold winters, accompanied by abundant snowfall; followed by highly variable springtime temperatures and precipitation (Miller et al, 2002). Snow typically covers the ground from November to April. Most of southern Manitoba receives 110-140 cm of snow annually (Encyclopædia Britannica, 2008). Annual precipitation varies from 360 mm to 560 mm, with about two-thirds occurring during May and September (Encyclopædia Britannica, 2008). As a result, Manitoba spring conditions tend to be cold and wet; often for prolonged periods of time. Under these conditions, dry bean production can be negatively affected (Wuebker et al, 2001).

The impact of a cold, wet soil was studied on soybean by determining soybean response and subsequent germination when imbibition water temperatures were too cold, leading to what was described as imbibitional chilling injury (OMAFRA, 2007b). It was determined that if the initial water temperature imbibed by soybean seeds was too cold—below 10°C—in the first 6-24 hours post planting then germination was lower compared to seeds that imbibed water that was warmed. These results were explained by a consequent disruption of the seed's membrane integrity and increased electrolyte leakage—the result of imbibitional chilling injury.

2.1.5.3 Salinity

Soil salinity can be an important constraint in bean production. Common bean is a highly salt sensitive species (Maas and Hoffman, 1977). Beans exposed to salts in the root zone exhibit impaired seed germination, poor nodule formation, delayed growth and development and reduced yields (Greenway and Munns, 1980). The main causes of soil salinity are excess water, poor soil drainage, irrigation and lack of vegetative cover. Although Manitoba does not practice irrigation for dry beans, excess spring moisture,

poor internal soil drainage, poorly structured soils and lack of vegetative cover outside the main cropping season occur.

2.1.5.4 Weeds

Dry beans are poor competitors with weeds (SPG, 2000; MAFRI, 2006). Bean competitiveness with weeds has been found to be positively associated with leaf area index (Wortmann, 1993). Dry beans, however, are short, slow growing and usually do not produce a dense canopy, especially in production systems where wide row spacing is used (MAFRI, 2006). Blackshaw (1991) found that dry bean yield was reduced by 13% and 77% with hairy nightshade densities at 2 and 100 plants m^{-2} of row. Wilson (1993) also found dry bean yields were reduced by 13% to 38% when proso millet was found at densities of 30 plants m^{-2}. Another study by Malik et al. (1993) found that in the absence of herbicide control, annual weeds reduced bean yield by 70%. Early weed control is most critical for maintaining dry bean yields. Studies by Blackshaw (1991) and Wilson (1993) determined the critical weed free period needed to to prevent yield reductions in dry bean, depending on the weed species, was between the first 3 to 5 weeks after planting. Broadleaf weeds, in general, are of particular concern. Current problem broadleaf weeds include redroot pigweed (*Amaranthus retroflexus*), common lamb's quarters (*Chenopodium album*), velvetleaf (*Abutilon theophrasti* Medic.), common ragweed (*Ambrosia artemesiifolia*) giant ragweed (*Ambrosia trifida*), smartweeds (*Polygonum spp.*), wild mustard (*Sinapis arvensis*), cocklebur (*Xanthium strumarium*) and nighshades (*Datura stramonium*) (OMAFRA, 2002). Weeds compete with beans for light, moisture and nutrients causing quality and yield loss (Sikkema et al, 2004).

Later-germinating weeds have minimal impact on yields and have relatively low production of weed seeds (OMAFRA, 2002), however, excess weeds present at harvest can affect harvest efficiency, increase mechanical damage to pods and increase quality losses by staining the beans (Sikkema et al, 2004)

2.2 Weed control practices in dry bean production

Most weed management programs for beans suggest using a combination of tillage, harrowing, soil incorporated herbicides, pre and post emergent herbicides (SPG,

2000, MAFRI, 2006) and sometimes include the suggestion of a fall planted cereal cover crop for early season control of grassy and broadleaf weeds.

2.2.1 Mechanical control

Mechanical practices for weeds control prior to planting are good for both row crop and solid seeded bean production systems. Following bean emergence, these strategies can only be continued in row crop production systems. Between-row cultivation usually only controls weeds found further away from individual plants, however, weeds found in close proximity to the beans are less accessible and pose the greatest threat (Amador-Ramirez et al., 2001). Mechanical weed control is best at low weed densities. At high weed densities, an additional management strategy, often herbicides, are necessary (Amador-Ramirez et al., 2001). Excess tillage can result in break down of soil aggregates and organic matter. Inter-row cultivation or harrowing can result in bean damage (OMAFRA, 2002).

2.2.2 Herbicides

Herbicide choices for beans are limited as there are but a few registered herbicides for weed control in dry bean (Soltani et al., 2004, Sikkema et al., 2004). Following the loss of metoburan and monolinuron, bean producers are limited to methenamid and imazethapyr for pre-emergent (PRE) weed control (Soltani el al, 2004). Post-emergent (POST) broadleaf herbicides are limited to bentazon and fomesafen (OMAFRA, 2002). Unfortunately, these herbicides do not provide reliable control for many troublesome weeds such as redroot pigweed, lambs quarters, smartweed and many others (OMAFRA, 2002).

2.3 Fall rye cover crops

"Cover crops are crops grown in the absence of a main crop or between main crop production periods as a means of protecting and enriching the soil". (Hartwig and Ammon, 2002).

2.3.2 Establishment and management

Cereal rye (*Secale cereale* L.), also know as fall/ winter rye or grain rye, has been recognized as one of the most prolific cereal cover crops (McLelland, 2007). Rye grows well on a range of soil types, although it prefers light or loamy soils (Bowman et al, 1998). Rye tolerates low temperatures and will germinate at temperatures as low as 1°C (Bowman et al, 1998), however, rye requires 4°C or greater temperatures for vegetative growth (McLelland, 2007). Rye tolerates low fertility, responds well in drought and is the most winter hardy of all cereals available to prairie farmers (Bowman et al, 1998). Rye establishes and grows well under cool fall temperatures and resumes growth quickly in early spring (Bowman et al, 1998).

Although fall rye can be seeded later than other cover crops, including winter wheat, to ensure good winter survival it is best to seed in the first two to three weeks of September (McLelland, 2007). This should give the fall rye at least 4 to 6 weeks to grow before the onset of vernalization and cold hardening, which usually occurs when daytime temperatures drop below 10°C and daylength is decreasing (McLelland, 2007). Seeding depths of 2 to 3.5 cm are best and seeding rates can be anywhere between 70-100 kg/ha (McLelland, 2007). Fall rye will begin growing the following spring in early April and accumulate most of its biomass during the month of May, therefore, monitoring the growth of the rye cover crop during this time it important so it can be terminated at an appropriate time. Terminating rye early can help minimize excess moisture depletion and nutrient tie ups (Bowman et al, 1998). Terminating rye late can deplete soil moisture and produce more residue than subsequent tillage can properly handle (Bowman et al, 1998).

Fall rye can both be terminated with tillage and incorporated or with herbicides and left as a surface mulch.

2.3.3 Benefits of rye cover crops in dry bean production

2.3.3.1 Erosion control

Soil is susceptible to erosion when there is no actively growing crop or residue layer to protect it. As a cover crop, fall rye can help protect the soils from wind and water erosion. Rye's top growth covers the soil surface and its deep root system, which

can extend 0.9 to 1.0 m depths below the soil surface (Verhallen, 2003a), unites soil particles, forming stable soil aggregates and holding them in place (Sarrantonio and Gallandt, 2003). Incorporation of rye cover crop biomass also leads to increases in soil organic matter or total soil organic carbon content following decomposition (Tisdall and Oades, 1980). Soil organic matter has been positively correlated to increased soil aggregate stability (Tisdall and Oades, 1982) as it operates as a soil binding agent. Lui et al (2005) working in British Columbia found that fall rye increased soil aggregation through release of acid-extractable polysaccharides from its root system, which contributed to the increased stability of 2-6 mm soil aggregates and increased soil aggregate mean weight diameter compared to control treatments. Residues from winter cover crops, used as mulch, help to prolong erosion control throughout the summer (Sarrantonio and Gallandt, 2003). Therefore, rye is an excellent cover crop for dry bean production. For example, cereal rye is adaptable to many soil types and areas of low fertility, it can easily be grown on the lighter textured soils commonly used for dry bean production. Due to its quick establishment in the fall and resumption in the spring (Bowman et al, 1998), it is available for erosion prevention during the most critical periods. Once rye is killed, residues remaining will extend this control period.

2.3.3.2 Water management

De Bruin et al (2005) working in Minnesota, found an actively growing fall rye cover crop used about 50 g/kg^{-1} of soil water (0-15 cm depth) during its early growth in May. Because rye is capable of depleting soil water (Bowman et al., 1998), growers sometimes use rye to reduce excess soil moisture before planting (OMAFRA, 2008; Osborne et al, 2002). The deep, fibrous root system of rye may create channels through the soil profile (Williams and Weil, 2004). These channels help water to move through soils that may be compacted or waterlogged (Williams and Weil, 2004). Residues left at or near the soil surface help to preserve moisture during the summer by reducing water evaporation and increasing water infiltration (Blackshaw, 2008, Teasdale, 1996). Timing for rye termination is, however, critical. Soil moisture depletion, by rye, may reduce stand establishment of a following dry bean crop if conditions during the growing season are dry. Although dry beans are susceptible to excessive moisture, lack of soil moisture

extending throughout the growing season can also reduce yields (SPG, 2000). A study by Wagger (1989) found that corn, a crop also highly sensitive to moisture stress at critical developmental stages, experienced greater yields following cereal cover crops when cover crop termination was executed early—7 to 14 days prior to corn planting—opposed to delayed termination.

2.3.3.4 Soil salinity

Rahmatullah et al. (2006) found a winter wheat cover crop was capable of lowering the water table leading to a decrease in soil salinity/sodicity compared to fallow plots. In addition, residues at the soil surface reduce evaporation (Bristow, 1988) and limit salts being drawn up.

2.3.3.5 Catch crop and nutrient cycling

Fall sown cereal cover crops can serve as nitrogen (N) catch crops by absorbing and storing N in their tissues through the winter months (Huntington et al, 1985). The amount of biomass produced by a cover crop governs to an extent the amount of N it will accumulate. Residue composition helps govern the rate and times of N release (Weinert et al, 2002). The cover crop can later provide this N to the subsequent crop through nitrogen mineralization provided that enough heat, moisture and microbial action are placed on the residues to promote decomposition and N release (MacDonald et al, 1995). The availability of N to the following crop, however, is largely influenced by rye termination time and its C:N ratio. The C:N ratio of rye increases as it matures, starting at 13:1 in the fall to 42:1 in early to late May (Clark et al., 1994). Since N mineralization is favored at C:N ratios less than 25:1 (Allison, 1966), terminating rye early, while it is still succulent is one way to minimize N tie-ups and promote more rapid N release from mineralization. Weinert et al (2002), working in Washington, investigated rye cover crop N release rates and effects on subsequent potato yields. They found that fall planted rye cover crop producing 4600 kg/ha and 2100 kg/ha of biomass had 133 kg/ha and 60 kg/ha, respectively, of N stored in their aboveground biomass at time of cover crop incorporation. At 25 days after planting potato and 62 days after rye incorporation, total inorganic N in the root zone was increased by 125 kg/ha compared to fallow control.

This increase in soil N availability following rye incorporation enhanced N accumulation by the potato crop through tuber initiation 47 days after planting. These researchers also found the net increase in soil inorganic N compared with bare fallow to be equal to or greater than the actual amount of N found in the rye shoot tissues, suggesting that considerable biomass decomposition and subsequent mineralization had occurred. Conditions known to favor decomposition and mineralization include rapidly rising spring temperatures followed by good moisture availability, low organic matter and well drained soils (Weinert et al, 2002).

Mid to late season N mineralization from rye cover crops may serve to provide extra N at the time of pod filling in dry bean, thus encouraging better yields.

2.3.3.6 Weed control

Studies have indicated that including fall cover crops in crop rotations result in reduced weed population densities and reduced total weed biomass due to rye's (1) potent toxicity — allelopathy— whereby chemicals are exuded through the root system and/or leached out of above-ground residues and (2) its high biomass production (Einhellig and Leather, 1988; Teasdale et al., 1991) whereby rye produces a dense canopy, which is more competitive than weeds for light, moisture and nutrients (Teasdale, 1996; Barnes and Putnam, 1983). In addition, residues at the soil surface intercept light, alter soil temperatures, moderate diurnal temperature fluctuations and act as physical barrier to emerging weeds (Barnes and Putnam, 1986; Teasdale and Mohler, 1993).

2.3.3.7 Bean establishment

Eckert (1988) and Liebl et al. (1992) reported reduced final soybean plant populations and yields, following delayed management of a rye cover crop. Liebl et al (1992) attributed reduced soybean stands to the increased amounts of rye biomass associated with the late termination which adversely affected soybean planting. Blackshaw (2008) observed a three to five day delay in dry bean development following a winter rye cover crop which he attributed to cooler soil temperatures resulting from rye's biomass. However, he did not observe any prolonged negative effects on plant population density, bean growth or yield. Liebman and Davis (2000) also observed a

lack of negative effects by winter rye on dry bean plant population density and De Bruin et al. (2005) observed that soybean establishment and yield following a rye cover crop, terminated early, were similar to controls.

2.4 Allelopathy in fall rye

2.4.1 Introduction to allelopathy

In nature, the struggle to survive often involves a fierce competition between two organisms occupying the same environment. This struggle is even more pronounced when competing organisms are confined to the spot from which they arose. With sessile organisms, such as plants, competitors pose a threat just by settling near one another, for as they grow they will compete with them for often scarce resources (Benayahu and Loya, 1981). In such competitive environments, it is an advantage to have toxic weapons to use in battle against other sessile opponents. In the plant world, these toxic weapons are known as allelochemicals. They work by hindering an opponent's ability to compete.

2.4.2 Allelopathy defined

Allelopathy is difficult to define and often difficult to separate from competition. Competition involves plants competing for a common resource while allelopathy involves plants interfering with each other more directly, through introduction of chemical compounds to the collective environment (Devi et al, 1994). Allelopathy, therefore, can be defined as an interference mechanism whereby plant materials, dead or alive, release chemicals, often secondary metabolites, which exert a negative effect on surrounding plants (Wardle et al, 1998). According to Rice (1984) an important point concerning allelopathy is that its effects are dependent on the addition of chemical compounds to the environment, thus separating it from competition which involves the removal or reduction of some factor required by plants sharing the same environment.

2.4.3 History of allelopathy

The ability of certain plant species to chemically interfere with the germination, growth or development of other plant species has been known for over 2000 years. Accounts of plants "exhausting" as opposed to "invigorating" the soil and destroying

weeds was noted by Theophrastus in 300 B.C. following his observations of events after chick pea cultivation, a plant now recognized as having allelopathic properties (Rice, 1984). In 1658, the botanist Browne reported in his book, "Garden of Cyrus" that "the good and bad effluviums of vegetables promote or debilitate each other" (Keynes, 1929). This well known phenomenon continued unnamed until 1937 when a botanist by the name of Molisch introduced the term allelopathy, derived from the Greek words allelon "of each other" and "pathos" to suffer (Rizvi et al, 1992). Collectively, this term refers to the injurious effect of one organisms upon another (Rizvi et al, 1992).

Since the introduction of this term, many plant species have been identified as having allelopathic properties. Fall rye (*Secale cereale*) is one of these species. Allelochemicals released from fall rye have been found to be responsible for reductions in population and biomass of several weed species (Einhellig and Leather, 1988)

2.4.4 The nature of allelochemicals

2.4.4.1 Biochemistry

Allelochemicals from rye are derived either from the acetate or shikimic acid pathways (Devi et al., 1994). Phenolic acids, beta-phenyl-lactic acid (PLA) and beta-hydroxybutyric acid (BHA), synthesized in the shikimate pathway, as well as two hydroxamic acids, 2,4-dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA) and 2(3H)-benzoxazolinone (BOA), have been isolated from rye tissues and exudates and found to be toxic to several weed species (Burgos and Talbert, 2000). Other secondary metabolites such as the phenolics ferulic acid and vanillic acid have also been identified. Their toxic effects, however, is less apparent (Burgos and Talbert, 2000).

Most allelochemicals are secondary plant metabolites, produced as byproducts of the primary metabolism pathways (Rice, 1984). The exact function of these secondary metabolites is not always known as they are not directly involved in plant growth, development or reproduction. However, several studies have determined that secondary metabolites play a role in defense reactions against herbivores and plant pathogens (Corcuera, 1993; Einhellig, 1995; Niemeyer, 1988). Rye allelochemicals are quite similar to a class of defense compounds, phytoalexins, which are synthesized by plants in

response to pathogen attack. The similarity between these compounds is that they are of related chemical classes, synthesized in the same biological pathways and have similar physiological and molecular modes of action (Devi et al, 1994)

2.4.4.2 Allelochemical release and fate in the environment

Allelochemicals in rye are present in several plant parts, including the roots, shoots and leaf blades (Rice, 1984). Their mode of release from tissues is through root exudates of living plants, leaching by the action of rain or snow on aboveground tissues and decompostition of residues on the soil surface (Barnes and Putnam, 1986). Barnes et al. (1985) found, however, that allelochemicals released from living rye shoots are less potent than those released from roots. Perez and Ormeneno-Nunez (1991) examining the release of hydroxamic acids from rye cultivars, found that the amount of DIBOA exuded by the roots was not proportional to the content of the compounds in the roots, which indicated that exudation of DIBOA is an active process under some form of internal regulation. This discovery led to research looking at the biotic and abiotic factors which could be driving the release of these hydroxamic acids.

Allelochemicals are reactive compounds and their phytotoxic effectiveness depends on how they react and interact with the soil environment. Soil type and texture, organic matter content, particle size distribution, pH and ion exchange capacity all influence the behavior and fate of allelochemicals in the soil (Rizvi and Rizvi, 1992). Typically, soils with higher clay and organic matter have greater absorptive powers which can bind these simple organic acids (allelochemicals), making them less available to the soil solution (Rizvi and Rizvi, 1992). Therefore, phytotoxicity of these organic acids is usually most evident when soils contain a mixture of sand and clay, organic matter content is moderate and soil ph is slightly acidic (Harper and Balke, 1981, Blum et al, 1985).

2.4.4.3 Factors affecting allelochemical production

Mwaja et al (1995) investigated the effect of an abiotic factor such as fertility status of the soil, on rye root exudate production. They found that concentrations of DIBOA and BOA in rye root exudates were highest when rye was grown under low (5

mM $N0_3^-$, 0.5 mM P and 3 mM K) or moderate (10 mM $N0_3^-$, 1 mM P and 6 mM K) nutrient availability compared to high (20 mM $N0_3^-$, 2 mM P and 12 mM K) availability. They went on to determine that rye tissues produced 210 μg/g and 21.5 μg/g when grown under low fertility and 128μg/g and 12.5 μg/g when grown under high fertility of DIBOA and BOA, respectively. This was further correlated to enhanced phytotoxicity as rye extracts from tissues grown under low fertility were more inhibitory to cress (*Lepidium sativum* L) and barnyard grass (*Echinochloa crusgalli*) germination and radicle elongation than extracts from rye tissues grown under high fertility. Other studies have found that DIBOA and BOA production also will increase under water stress (Barnes et al, 1985).

Studies looking at biotic factors affecting allelochemical production have determined that defoliation and disease will lead to increased allelochemical production. Collantes et al (1997) found that repeated defoliation of rye seedlings led to an increase in the allocation of hydroxamic acids to the roots and root exudates. It was suggested that this increase in hydroxamic acid exudation might lead to an advantage in resource acquisition for the regeneration of lost biomass if neighboring plant species were hindered in their competitive abilities.

Few studies specific to rye have looked at how disease plays a role in allelchemical production. Rice (1984) and Einhellig (1995) hypothesized that pathogens enhance their host's allelopathic ability. Since then, Mattner and Parbery (2001) found that the presence of crown rust (*Puccinia coronata*) on perennial ryegrass (*Lolium perenne*) suppressed the growth of neighboring white clover (*Trifolium repens*) compared to non- infected controls. This paper was one of the first to prove that diseased plants suppress the growth of other neighboring plant species.

2.4.4.4 Toxicity and selectivity of allelochemicals

The negative effects of rye on many weed species have been determined in both field experiments looking at weed densities and biomass under varying amounts of rye biomass, followed by growth chamber and bioassay experiments looking at weed seed germination and seedling development.

Some physiological effects of allelochemicals on susceptible weed species include inhibited enzyme activity, reduced cell division in the roots, interactions with plant hormones, reduced photosynthetic rates, effects on nutrient uptake and allocation, reduced respiration and overall reduced seed germination (Rice, 1984; Devi et al, 1994; Friebe et al, 1995). Studies specific to rye have reported that weed species emerging through rye residues were chlorotic and stunted, even though nutrient status was optimal (Kruse et al., 2000). Barnes and Putnam (1986, 1987) reported that apical root meristems of lettuce were chlorotic and root growth of the seedlings was reduced when the seeds germinated in the presence of rye residues.

Studies by Reberg-Horton et al. (2005) and Rice et al. (2005) determined that rye's toxicity is most pronounced in younger tissues, whereby, total concentration of hydroxamic acids generally declined with age. Therefore, greater weed suppression found under greater amounts of biomass is most likely attributed to physical suppression as opposed to increased toxicity by rye.

The fact that allelochemicals produced by rye have strong species specificity provides good evidence as to the selective nature of rye exudates on the weed community. Studies have found that dicotyledons (broadleaf weeds) are more sensitive than monocotylendons (grass weeds) to DIBOA, BOA, PLA and HBA (Barnes and Putnam, 1987). Some of the main and most repeatedly inhibited species are red root pigweed *(Amaranthus retroflexus)*, lamb's quarters *(Chenopodium album)*, lettuce *(Lactuca sativa),)*, green foxtail *(Setaria viridis),* barnyard grass *(Echinochloa crusgalli)*, wild oat (*Avena fatua*) and goosegrass (*Eleusine indica*) (Barnes and Putnam, 1986,1987; Putnam and DeFrank, 1983; Shilling et al, 1985; Burgos and Talbert, 2000; Moonen and Barberi, 2005; Perez and Ormemeno-Nunez, 1993, Teasdale et al.,1991; Reberg-Horton et al., 2005; Blackshaw, 2008). Large crabgrass (*Digitaria sangiunalis)* is often found to be less inhibited by rye (Burgos and Talbert, 2000; Teasdale et al., 1991; Reddy et al., 2003). A study by Chase et al. (1991) looked at the effects of allelopathic compounds DIBOA and BOA produced by rye on garden cress (*Lepidium sativum*) barnyard grass (*Echinochloa crusgalli*), cucumber (*Cucumis sativus*) and snap bean (*Phaseolus vulgaris L.*). They found that the larger and deeper seeded species were less sensitive to rye's allelochemicals. They determined this decreased sensitivity was likely due to a dilution

effect, whereby high concentrations of allelochemicals would be found near the soil surface where the smaller seeded species typically germinate, and lower concentrations at increasing depths. They concluded, therefore, that selectivity of allelochemicals produced by rye can be achieved based on seed size and seed placement, much like the selectivity of synthetic herbicides.

2.4.5 Allelopathy in fall rye and winter wheat

2.4.5.1 Allelochemicals identified

The allelochemicals DIBOA (2,4-dihydroxy-1,4(2H)-benzoxazin-3-one) and its breakdown product BOA (2(3H)-benzoxazonlinone) are the main hydroxamic acids found in rye tissues and exudates, while DIMBOA (2,4-dihydroxy-7-methoxy-(2H0-1,4-benzoxazin-3(4H)-one) and its breakdown product MBOA (6-methoxy-benzoxazolin-2(3H0-one) are the main hydroxamic acids in winter wheat (Copaja et al, 1999, Macias et al, 2005). DIMBOA and DIBOA differ only by a methoxy group found in the former (Virtanen and Hietala, 1960). Similar to rye, wheat allelochemicals are present in root and shoot tissue and in the secretions from roots of living plants (Petho, 1992,Copaja et al, 1999).

2.4.5.2 Mode of action studies

Studies have found that the hydroxamic acids DIBOA and BOA from rye and DIMBOA and MBOA, the main hydroxamic acids in wheat, adversely affect seed germination and radicle elongation through inhibition of enzyme activities (Friebe et al, 1997; Kato-Noguchi and Macias, 2006). Impaired enzyme activity, as identified by Rice (1984), is one of the primary targets for allelopathic activity. Friebe et al (1997) found that DIBOA, BOA and DIMBOA applied to seeds of *A.sativa* and *V.faba* resulted in inhibition of the plasma membrane H^+ATPase, which correlated to a decrease in germination and radical elongation of test species. H^+APTase is a plasma membrane enzyme that is responsible for hydrolyzing ATP and translocating protons from the cytosol into the apoplastic space. The resulting acidification of this process is used to promote secondary nutrient transport and cell elongation, both of which are crucial in

seed germination since emergence of the radical requires growth of embryonic cells. It was hypothesized by Friebe et al (1997) that reduced activity of this enzyme created an alteration in nutrient transport and absorption leading to decreased cell growth. Similar investigations by Sanchez-Moreiras et al (2001) found that lettuce seeds treated with BOA experienced significantly reduced germination and radical growth compared to controls. Furthermore, they found that lettuce (*Lactiva sativa*) roots treated with BOA showed an increase in membrane permeability and significant release of the ions studied ($N0_3$, $P0_4^{3-}$, $S0_4^{2-}$, Ca^{2+}, NH_4^+) indicating that BOA was degrading the plasma membrane.

Another study by Kato-Noguchi and Macias (2005) assessing the effects of MBOA, a hydroxamic acids specific to wheat, on lettuce, found that seeds treated with this phytochemical exhibited reduced germination compared to controls. Further analysis determined the reduction in germination of lettuce seeds to be a result of an inhibitory action of this hydroxamic acid on α-amylase activity in the seeds. Alpha (α) amylase enzyme is responsible for the breakdown of reserve starches in the endosperm into soluble sugars that serve as a food source for the seed (Perata et al, 1992). This enzyme is considered essential for seed germination and seedling growth (Perata et al, 1992). A second study by Kato-Noguchi et al (2006) applied this same phyochemical to cress (*Lepidium sativum*) seeds and found similar results on α-amylase activity and subsequently reduced seed germination. No literature was found that indicated DIBOA and BOA, allelochemicals from rye, have this effect on α-amylase activity.

2.4.5.3 Relative phytotoxicity study

The study by Friebe et al (1997) found that DIBOA, BOA and DIMBOA all significantly inhibited plasma membrane H^+ATPase activity in seeds of *A.sativa* and *V.faba* causing reduced germination and radicle elongation. DIMBOA, however, showed greater inhibition on both enzyme activity and subsequent germination and radical elongation compared to DIBOA and BOA. DIMBOA and DIBOA differ only by a methoxy group found in the former. The reactive nature of hydroxamic acids to sulphydryl groups is thought to be one reason why they have inhibitory effects on enzymes (Queirolo et al, 1983). Friebe et al (1997) attributed the greater effect, by DIMBOA, to the presence of its methoxy group which enhanced its reactivity, thus

making it more inhibitory to the plasma membrane enzyme H^+ATPase compared to DIBOA and BOA.

2.4.6 Common bean defense strategy to allelopathy

2.4.6.1 Introduction

It has been said that certain plant species have adapted strategies to survive allelopathy through metabolization or detoxification of absorbed allelochemicals by constitutive or inducible pathways (Sicker et al, 2003). Metabolization and detoxification are common ways by which crop plants survive herbicide applications, insect and pathogen attack and, therefore, it has been suggested that similar strategies are employed in these adapted species following allelopathic attack (Sicker et al, 2003). Additionally, biotic stresses such as pathogen attacks or abiotic stress such as metal toxicity have been found to induce the synthesis of proteins, sometimes novel, by plants in response to these stresses (Romero et al, 2001).

2.4.6.2 Defense proteins

The common bean seed contains several kinds of proteins (Sales et al, 2000). Among these are storage proteins such as proteinase inhibitors, lectins, lectin-like proteins, ribosome-inactivating proteins, glucanases, chitanases and α-amylase inhibitors (Sales et al, 2000). These proteins are associated with defense mechanisms developed to protect the plants from insects, herbivores and pathogens (Sales et al, 2000).

2.4.6.3 Bean response to allelopathic stress studies

Although no literature was found testing allelochemicals produced by rye or wheat on bean seed germination, studies testing extracts from other allelopathic plants on beans were found. Romero-Romero et al (2002) found that extracts from two alleopathic plants, *S. deppei,* and *S. adenophora* had differential effects on radicle growth and root cytoplasmic protein synthesis of common bean (*P. vulagris*). They showed that extracts from *S. deppei* inhibited radicle growth by 70% and produced no effect on the expression of root cytoplasmic proteins. Extracts from S. *adenophora*, however, were found to have

no effect on radicle growth, yet revealed an altered expression of 10 proteins, whereby 7 were increased. The authors suggested this increase in proteins may have been in response to allelopathic stress and possibly related to activation of defense mechanisms in common bean. A similar type of study by Cruz-Ortega et al. (2002) assessed the effects of allelopathic stress produced from the aqueous leachates of *Callicarpa acuminatea* previously reported to exhibit a strong allelopathic effect on *Amaranthus hypochondriacus* and *Echinochloa crusgalli* (Anaya and del Amo, 1999), on germination and radicle growth of several crop species, including common bean. Unlike tomato seeds also subjected to these extracts in this study, common bean did not experience reduced germination or radicle growth. Protein expression analysis of treated bean roots showed that of 5 proteins whose expression was altered, all were increased. Micro sequencing analysis of the proteins expressed in bean roots, induced by extracts of *C. acuminata*, revealed one protein to show 99% similarity with that of an α-amylase inhibitor of other *P. vulgaris* varieties. An α-amylase inhibitor is a seed storage protein in beans associated with defense mechanisms against insects and pathogens (Sales et al, 2000). The authors of this study hypothesized that since α-amylase inhibitor is increased 2-fold in beans during treatment with *C.acuminata* extracts, this suggests the protein may actually be a general defense response in beans, not necessarily specific to insects or pathogens. They also proposed the expression of this protein might well be responsible for inducting further defense mechanisms or systems in response to alleopathic stress.

Cruz-Ortega et al (2002) found that aqueous extracts from *C.accuminata* reduced germination and radicle elongation in some crop species, however, not in common bean. These authors attributed this lack of effect to an α-amylase inhibitor defense protein, induced in response to allelopathic stress from the extracts of *C.accuminata*. Friebe et al (1997) found that DIMBOA, the hydroxamic acid specific to wheat, showed greater inhibition to germination and radicle elongation in test species compared to DIBOA and BOA— the main hydroxamic acids in rye. They attributed DIMBOA's stronger inhibition to the presence of a highly reactive methoxy group, thought to be more inhibitory to an enzyme needed to maintain stability of seed plasma membranes and subsequent seed functions.

2.4.7 Methods in allelopathy

Allelopathy is difficult to demonstrate using field experiments. Therefore, bioassays are a useful tool to prove that phytochemicals released from one plant induce a negative or inhibitory effect on another plant. Common methods seen in allelopathy bioassay experiments, involve either cold or hot water extractions on both ground and whole plant tissues, often heated and agitated for several hours and then either filtered or centrifuged to remove plant materials, thereby producing a crude aqueous extract (Burgos and Talbert, 2000, Reherg-Horton et al., 2004; Barnes and Putnam, 1986; Barnes et al, 1987). The crude aqueous extracts are then typically applied to test species varying from 1 ml to 4ml aliquots (Putnam and Duke, 1978; Burgos and Talbert, 2000, Burgos et al, 1999). Control treatments consist of distilled or ionized water applied to the same test species in equal amounts to the aqueous extracts (Burgos and Talbert, 2000, Burgos et al, 1999). Following a set incubation time, test species are removed and total percent germination is determined. Germination or seedling growth inhibition resulting from applications of rye extracts can be used to prove the presence of allelopathy or to determine it to be one of the mechanisms controlling weed suppression.

2.5 Competition and physical suppression by fall rye

Rye cover crops affect weeds through competition for light, nutrients and moisture. Physical suppression by rye's residues can also alter light transmittance, temperature and moisture regimes, of which many weed species have specific requirements for germination.

2.5.1 Weed seed dormancy

Often, weed seeds possess dormancy mechanisms that prevent them from germinating at times when environmental conditions for survival are not optimal (Harper, 1977). Breaking weed seed dormancy often requires specific environmental cues such as light, temperature and moisture at the right time and in the proper dose (Harper, 1977). Failure of the environment to provide these specific cues results in innate sensing of the seeds that their local environment may not be favorable and wait for more Therefore, they lie in wait—dormant—for more favorable times and conditions (Battla et at, 2000).

2.5.2 Modifications by rye to the weed microenvironment

2.5.2.1 Light interception

The radiation found under a canopy or residue layer has two components: unfiltered daylight, passing through gaps in the residue layer; and filtered or attenuated daylight, of which the spectrum has been altered by the residues through the processes of absorption, reflection or transmission (Smith and Morgan, 1981). Of the total quantity of radiation directed at the soil surface, only a portion will actually reach its destination unfiltered, under a crop canopy or crop residues. Due to albedo, some of the incoming radiation will be reflected. Song (1999) found that an average winter wheat field had an albedo of between 0.2-0.4, therefore, 20-40% of the incoming radiation was being reflected by the wheat crop. This reflected solar radiation is rich in PAR or photosynthetic active radiation (400-700 nm wavelengths), the spectrum of which is required for both seed germination and plant growth (Taiz and Zeiger, 2002). Therefore, the quantity of unfiltered daylight reaching the surface under residues is restricted to passage by holes in the canopy or residues (Smith and Morgan, 1981). Seeds below the surface in these dark areas will not perceive light and if they are a highly light dependent species, germination will not occur (Taiz and Zeiger, 2002). The portion of light that makes its way through is the filtered, or attenuated daylight, altered by the chlorophyll located in the growing cover crop tissues or fresh residues, thereby, producing a typical shadelight spectrum. This shadelight spectrum lacks much of the photosynthetically active radiation (PAR), as chlorophyll strongly absorbs the blue (350-500 nm) and red (600-700 nm) wavelengths (Battla et al, 2000). Chlorophyll, however, is transparent to the far-red (700-800 nm) wavelengths; located outside of PAR. This reduction in red light (R) and increase in far red light (FR) leads to a reduction in the R:FR ratio (Kruk et al, 2006). These spectral changes in the light environment can be perceived by weed seeds at the soil surface through photoreceptors, particularly those from the phytochrome family (Battla et al, 2000). Phytochrome is a photoreceptor protein involved in several physiological processes including light mediated seed germination responses (Taiz and Zeiger, 2002). When exposed to red light (R), phytochrome (P) will absorb this light and convert to Pfr, establishing the active form for germination. When exposed to far red

(FR) light, phytochrome will absorb it and convert to Pr, establishing the inactive form for germination (Battla et al, 2000). The R:FR ratio of unfiltered daylight is approximately 1.2 (Kruk et al, 2006). It has been shown that several weed species such as wild mustard (*Sinapsis arvense)* and broad leaved plantain (*Plantago major)* require a R:FR ratio between 0.6-0.8 to achieve 100% germination for broad leaved plantain and 75% germination for wild mustard (Frankland, 1981, Battla et al., 2000). It has also been shown that under a wheat canopy this ratio can be as low as 0.2- 0.49 (Frankland, 1981) depending on canopy densitiy. The physiological importance of sufficient Pfr is most pronounced at the time of imbibition— water uptake— by the seed since Pfr is required to photoactivate the genes for amylase, an enzyme used to break down and mobilize the stored food reserves in the seed causing it to sprout (Raven et al, 2003). Without sufficient Pfr, germination will not occur in light dependent species.

Futhermore, most weed seeds are not found right atop the soil surface. Typically, they are found at several millimeters (mm) depth below the soil surface. A study by Woolley and Stoller (1978) found that light penetration through a Drummer silty clay loam and a Broomfield sand, measured spectophotometrically, was less than 1% of the incident light that penetrated 2.2 mm at any wavelength between 350-700 nm for ped sizes up to 1mm. They determined that both soils transmitted more of the longer wavelengths (FR) compared to the shorter wavelengths (Blue). It was also determined that the quality of light decreased with increasing depths in both soils. To ascertain the biological implications of this, they used light-sensitive lettuce (*Lactuca sativa*) seeds planted at the soil surface, 2mm and 6 mm depths below the soil surface and measured percent germination at each depth compared to dark controls. From their germination results at the three depths in both soils, they concluded that at a 2 mm depth, germination would ensue following 1 full sunny day for seeds comparable in sensitivity to lettuce. Most weed seeds, however, are located at greater depths than 2 mm since they can be moved vertically through the soil profile of loose-textured soils with percolating rain water, buying action of soil cast by earthworms, hoarding activities of birds and rodents and cultivation (Harper, 1977). They also estimated that several sunny days would not have been sufficient to induce full germination at the 6mm depths in the selected soils, partly due to the quantity of light reaching that depth and partly because the quality of

light at that depth would be so strongly biased toward far red that germination would most definitely be inhibited. It would appear, therefore, that seeds found under a canopy or residue layer and located at depths below 2 mm, if light dependent, may not receive sufficient light to induce germination.

Some common weed species located in Manitoba and across the Prairies which are light dependent or light sensitive species include: red root pigweed (*Amaranthus retroflexus),)* yellow foxtail *(Seteria glauca),* lamb's quarters*(Chenopodium album),* stinkweed *(Thlaspi arvense)* and barnyardgrass (*Echinochloa crusgalli)* (Anderson, 1968; Baskin and Baskin, 1998).

2.5.2.2 Residue effects on temperature and moisture

Many weed seeds require specific temperatures or daily fluctuating temperatures to promote germination (Teasdale and Mohler, 1993). Many studies have shown that thermal regimes under a residue layer can differ considerably compared to that of bare soils (Horton et al, 1994, Horton et al, 1995, Bristow, 1988). Often, daytime soil temperatures are much lower under residues and fluctuate less. For example, Bristow (1988) found that under dry conditions, soil temperatures were 10°C cooler under a mulch treatment than those measured at the bare soil surface. The modifications in soil temperature under surface residues are intimately tied with soil moisture and, therefore, must be discussed together.

In temperate climates, much like those of the Prairies, springtime conditions usually consist of cold, wet soils due to low levels of solar radiation and snow melt (Horton et al, 1995). Because of this, the soil will only begin to warm after the excess moisture has been removed (Horton et al, 1994). Surface residues have a higher albedo — the percentage of total radiation that is reflected rather than absorbed — compared to a bare soil, leaving less total energy available for soil evaporation and subsequent soil warming. The consequence of slowly warming soil temperatures may result in delayed emergence of some weed species with flexible dormancy status (Teasdale and Mohler, 1993).

The amount of surface residues also affects the total net radiation transmitted to the soil surface. As the quantity of residues increases, the total net radiation transmitted

decreases (Tanner and Shen, 1990). In addition, this reduced heat load on a covered soil reduces its maximum daily soil temperature compared to a bare soil. A study by Bristow (1988) comparing daily maximum soil temperatures at a 2.5 cm depth below a bare soil and a horizontal residue layer, found, that across a 12-day period, there were significant differences between treatments. Maximum soil temperatures for the bare soil treatment ranged from 32°C to 42°C, while the residue treatment ranged from 29°C to 33° C. For one weed species in particular, redroot pigweed, this altered temperature regime is highly consequential. According to one source, the optimal temperatures for germination of redroot pigweed are between 35°C to 40°C (Anderson, 1968). Relating this to the maximum temperatures in Bristow's experiment, we see that successful germination of redroot pigweed would be favored only in the bare soil treatment where temperatures reach those required. The residue treatment, however, never rose above 33°C, thereby, falling short of redroot pigweed requirements in the range of 35° to 40°C for terminating dormancy.

Although net radiation is reduced for a covered soil surface and was found to result in decreased maximum soil temperatures, some radiant energy still penetrates through the residues and into the soil, causing both soil temperature increases and drying due to evaporation. Evaporation cools its surrounding environment and in turn gives off heat.

Residues are good insulators, and because of this, trap the heat being released through these energy exchanges (Horton et al, 1994). This trapping of heat leads to a more stable thermal environment under the residues, due to a reduction in diurnal or daily temperature fluctuations than would be seen in a bare soil (Horton et al, 1994). The biological implications of this on germinating weed seeds relates to disruptions, or lack thereof, of fluctuating diurnal temperatures. The same study by Bristow (1988) that examined daily maximum soil temperatures also examined the diurnal trends in a 2.5 cm depth in both wet and dry soil conditions below a bare and horizontal residue cover treated soil. It was found that under wet conditions, both the bare and residue covered soils, across a 24-hour period, had daily temperature fluctuations of about 8°C. Most weed species with a temperature amplitude requirement rely on at least a 10°C amplitude change (Teasdale and Mohler, 1993). Any species falling under this category, therefore,

would have reduced germination under wet soils in either treatment. Under dry conditions, however, the bare soil and residue covered soil segregated over this 24-hour period, resulting in differences in daily temperature fluctuations spanning across temperature increments of 20°C for the bare soil and 11°C for the residue covered soil. For one particular weed species, stinkweed (*Thlaspi arvense)*, alternating daily temperatures lead to more favorable germination than constant temperatures. Laboratory germination tests found that alternating temperatures by 15°C resulted in the greatest germination percentages (Anderson, 1968). Placing this species in the context of Bristow's work would most likely result in greater germination in bare soil since the 15°C fluctuation requirement by stinkweed would only be received in this treatment. The residue covered soil, with reduced daily temperature fluctuations compared to bare soil, may not be enough to stimulate full germination in stinkweed if sensitivity to this temperature requirement is high.

2.5.2.3 Mechanical barrier

Not all weed seeds require light to germinate. Not all weed species are sensitive to disruptions in temperature or moisture regimes in the weed microclimate. At this point, the residue layer takes on another role. It becomes, in itself, a physical and mechanical barrier to the pure light above (Teasdale and Mohler, 1993). Although the weed seeds may have germinated, they are still dependent on the food reserves of their seeds for growth, as the quality of light below the residues is too poor for photosynthesis. In this situation, weight, density and surface area of the residue layer may be sufficient to suppress further weed seedling shoot extension past this barrier, causing the seedlings to run out of food and die (Bosy and Reader, 1995).

3.0 MATERIALS AND METHODS

3.1 Site establishment

Field experiments in 2006 were conducted at the University of Manitoba Plant Science Research Station in Carman, MB and the Proven Seed Research Farm in Rosebank, MB. In 2007, field experiments were conducted at the University of Manitoba "Point" research station in Winnipeg, MB and the Proven Seed Research Farm in Rosebank, MB. Establishment of experimental areas began with fall seeding of a fall rye cover crop in 2005 and 2006 (Table 3.1).

Table 3.1. Fall rye cover crop cultivar, month seeded and seeding rate at each site year location

Site location	Year	Cultivar	Month	Seeding rate
Carman, MB	2005	Remington	September	~ 100 kg/ha
Rosebank, MB	2005	Remington	September	~ 85 kg/ha
Winnipeg, MB	2006	Remington	October	96 kg/ha
Rosebank, MB	2006	Remington	September	~ 100 kg/ha

The following spring, soils at experimental sites were randomly sampled at the 0-15 cm and 15-60 cm depths then sent to Agvise Labs for analysis. Soil Association, sampling dates, soil report analysis and previous crop history for each site-year can be found in Table 3.3.

The experimental design for each site was a randomized complete block in a split plot arrangement. All treatments were replicated four times. Treatments were as follows: Main plot treatments were fall rye or control; subplots were early or delayed soil tillage and subsubplots were in-crop herbicide or control. Mainplots at Carman in 2006 were established into 36m x 8m, subplots into 12m x 8m and subsubplots into 4m x 8m. Mainplots at Rosebank in 2006 were set up into 20m x 10m main plots; 6m x 10m sub plots and 2m x 10m subsubplots. In 2007, main plots at Winnipeg were 28m x 6m, subplots were 12m x 6m and subsubplots 4m x 6m; at Rosebank mainplots, subplots and subsubplots were 20m x 10m, 6m x 10m and 2m x 10m, respectively.

3.2 Tillage and rye termination

Tillage dates, rye's developmental stage and rates of incorporated biomass for each site-year are available in Table 3.4.

In 2006, early and late tillage treatments each received a single pass using a 1.8 m wide rotovator at their respective times (Table 3.4). However, in 2007 substantially more rye biomass was present in late termination treatments; therefore, an additional pass was required to incorporate the biomass. To prevent confounding results, delayed tillage treatments without rye and all early tillage treatments also received an additional pass with the rotovator.

3.3 Dry bean seeding

Dates, seeding rates and fertilizer rates are summarized in Table 3.2 for each site-year.

Upon completion of late tillage treatments, all plots were solid seeded with Envoy navy beans using a Bourgault air seeder at 15 cm row spacing to a 4 to 5 cm depth. Nitrogen and phosphorus fertilization was added at time of bean seeding. Nitrogen was placed in a mid row band and phosphorus was placed below the seed.

Table 3.2. Dry bean seeding date, seeding rate and fertilization at four site-years

Site location	Year	Seeding rate	Seeding date	N applied (46-0-0)	P_2O_5 applied (11-52-0)
Carman, MB	2006	90 kg/ha	May.26	92 kg/ha	32 kg/ha
Rosebank, MB	2006	88 kg/ha	June.2	204 kg/ha	32 kg/ha
Winnipeg, MB	2007	89 kg/ha	June.1	170 kg/ha	NA[z]
Rosebank, MB	2007	92 kg/ha	June.5	170 kg/ha	NA

z NA= not applied

3.4 Herbicide applications

In 2006, both Carman and Rosebank were sprayed with Roundup (Weathermax) at a rate of 2.5 L/ha (0.9 kg a.i.ha^{-1}) the day after bean seeding to kill any standing rye.

Table 3.3. Soil association, sampling date and soil nutrient status and previous crop history at each experimental site

Site location	Year	Soil Association	Sampling date	Soil Nitrate (kg/ha)	P	K	S	pH	% OM	Previous crop
					----------kg/ha-------					
Carman, MB	2006	Hibsin fine sandy loam	May.11	62	32	427	nd[z]	5.4	4.3	wheat
Rosebank, MB	2006	Gretna clay	May.11	38	74	1385	nd	nd	nd	barley
Winnipeg, MB	2007	Riverdale silty clay	May.3	103	84	1214	114	7.2	4.0	oat
Rosebank, MB	2007	Gretna clay	May.3	53	64	902	130	7.4	3.3	oat

z nd = no data

Table 3.4 Date, developmental stage and incorporated biomass of the fall rye cover crop at two termination times

Termination time		Carman 2006	Rosebank 2006	Winnipeg 2007	Rosebank 2007
Early	Date	May.17	May.17	May.18	May.16
	Developmental stage	4 leaf, 3 tillers	4 leaf, 1 tiller	4 leaf, 3 tillers	5 leaf, 3 tillers
	Biomass (kg/ha)	1465	555	1085	1570
Late	Date	May.26	June.1	June.5	June.1
	Developmental stage	jointing	5 leaf, 3 tillers	heading	booting
	Biomass (kg/ha)	3645	1245	5220	4162

Due to the extra tillage pass in treatments at sites in 2007, this rye control measure was not necessary and, therefore, not implemented.

Following early season weed counts, in-crop herbicides were applied to designated plots. In 2006, Carman and Rosebank were sprayed with a tank mix of Basagran at 1.75 L/ha (bentazon at 0.84 kg a.i. ha^{-1}), Reflex at 0.58 L/ha (fomesafen at 0.14 kg a.i. ha^{-1}) and Assist adjuvant at 2.0 L/ha for broadleaf weed control. Five days later Poast Ultra was sprayed at 0.47 L/ha (sethoxydim at 0.21 kg a.i. ha^{-1}) with Merge adjuvant at 0.5%v/v for grass weed control. At this time, the bean crop was at the third trifoliate stage (MAFRI, 2007a).

In 2007, wet field conditions at both sites and flooding of the surrounding area at Rosebank, prevented timely herbicide applications. Due to the delay, weeds, particularly redroot pigweed, were quite advanced. Therefore, a higher rate of Basagran was used. Also, the bean crop had advanced to the fourth and fifth trifoliate stage, therefore, no Relfex was tank mixed with Basagran. As a result, Winnipeg and Rosebank were sprayed only with Basagran at 2.25 L/ha (bentazon at 1.08 kg a.i. ha^{-1}) with Assist adjuvant at 1.0 L/ha. Six days later, Poast Ultra was applied at 0.47 L/ha (sethoxydim at 0.21 kg a.i. ha^{-1}) with Merge adjuvant at 0.5%v/v.

3.5 Measurements

3.5.1 Rye biomass

Rye biomass was determined in all rye plots immediately prior to all tillage treatments. Two 1/4 m^2 biomass samples were collected from each plot, dried at 70°C for 72 hours and weighed. At this time, four rye plants were randomly sampled from each plot, staged, and then averaged to be used for determining cover crop developmental stage. Seedlings were staged based on leaf count and tillers while subsequent staging was based on major developmental changes including jointing, booting and heading.

3.5.2 Soil moisture

To determine cover crop water usage prior to bean seeding, gravimetric soil moisture samples were collected from both early and late rye termination treatments, at

the time late termination treatments were executed. Soil depths of 0-10 cm, 10-30 cm and 30-50 cm were sampled, weighed, dried at 60°C for five days and reweighed. The difference between the two weights divided by oven dry soil weight was the gravimetric soil water content.

3.5.3 Weed population density

Early season weed densities were determined by taking weed counts in each subplot following full dry bean emergence. Weed counts were taken late June at Carman and Rosebank in 2006 and early July at Winnipeg and Rosebank in 2007. These times coincided with majority the of weeds emergence

At Carman, weed counts were made using 1/4 m^2 quadrats and 1/10 m^2 quadrats, where weed densities were higher. At Rosebank 1/10m^2 quadrats and 1/100 m^2 quadrats were used due to high grass weed densities. At 2007 sites, weed densities were comparatively lower, therefore, 1/4 m^2 quadrats were required.

Four counts were taken per subplot using randomly placed quadrats, in all site-years. All weed species were identified and recorded separately, then removed from the soil.

3.5.4 Dry bean density and development stage

In all site-years, following bean emergence, four permanent, randomly placed 1/4 m^2 quadrats were established in herbicide control treatments in all tillage subplots. These areas were used for crop density and development monitoring.

In 2006 at Carman and Rosebank, dry bean population densities, at full bean emergence, were determined by counting the number of bean plants found in these permanent quadrats. In 2007, at Winnipeg and Rosebank, bean enumeration was done by randomly placed 1 m^2 quadrats in the herbicide control treatments of all tillage subplots.

In 2006 and 2007, bean staging, a measure of growth and development changes in response to treatments, was assessed using the permanent quadrats. Bean development at sites in 2006 was assessed every three to four days for approximately two weeks. Due to extremely wet field conditions in 2007, only two measurements were possible. Bean plants were staged based on a decimal scale of 0.1-1.0 for the first trifoliate; 1.1-2.0 for

the second trifoliate and continuing up to the fourth trifoliate using a similar scaling system.

3.5.5 Dry bean height

Bean height was measured at full bloom from the base of the plant to the top of the apical flower, in all site-years using a ruler. Four randomly chosen plants were measured from all treatments to determine the effects of rye, time of tillage and herbicide applications on dry bean height.

3.5.6. Accumulated weed and bean biomass

Accumulated biomass was measured when the bean crop was beginning to mature in 2006 by harvesting four random 1/4 m^2 samples from all individual plots on August 29th and 30th at Carman and Rosebank, respectively. In 2007, at a similar crop stage as 2006, one randomly placed 1 m^2 quadrats were used to collect biomass on August 15th and 16th at Winnipeg and Rosebank, respectively.

Once biomass was collected, individual plot samples were sorted by species, dried at 70°C and weighed six days later.

3.5.7 Dry bean yield and seed weight

Dry bean yield data was collected in 2006, at full bean maturity, by first harvesting three random 1m^2 samples from all plots on August 30th at Carman and September 14th Rosebank. Due to deer interference in plots at Winnipeg, bean yield samples were collected before the crop had reached full maturity. Rosebank samples in 2007 were collected at full maturity in the dry bean crop. Nevertheless, four 1m^2 samples from Winnipeg and three 1m^2 samples from Rosebank were collected on August 23 and September 4th, respectively.

Dry bean samples were air dried indoors for seven days in 2006 before threshing using a mechanical hand threshing machine. In 2007, samples were first dried outdoors for ten days, and then transferred inside for one day before being put through a Wintersteiger combine running at 350 rpm, with front concave opening set at 10mm, rear opening set at 5 mm and chaffer sieve opening and shoe sieve openings set at 1.2 and 1 cm, respectively.

Bean seed weights, determined from threshed samples from 2007 sites, were first cleaned and then 200 seeds were randomly chosen and hand counted from individual samples before being weighed and data recorded.

3.6 Bioassays with cover crop extracts

Greenhouse grown rye *cv.* Remington and field grown rye *cv.* Remington harvested from plots at Winnipeg and Rosebank in 2007 were randomly sampled at the four leaf stage. For the variety trial experiment, fall rye *cv.* Remington, winter triticale *cv.* Pika and winter wheat *cv.* Buteo were seeded the previous fall in a completely randomized design and replicated four times. The following spring, plants were hand harvested and randomly sampled at the four leaf stage. Samples were treated similarly in all experiments beginning with tissues being cut into 5 cm sections to a total weight of 40 grams. The cut tissues were treated with liquid nitrogen and coarsely ground using a mortar and pestle with a total of 50 pounds with the pestle per sample. The ground tissues of each variety were then separately transferred to individual 500 ml Erlenmeyer flasks, diluted using distilled water in a 1:10 w/v (Burgos and Talbert, 2000), covered and put onto a shaker set at 37°C at 200 rpm for a period of 24 hours. At the end of the incubation period, the flasks were removed and the extracts separated from the tissues using a vacuum filter lined with Whatman No. 1 qualitative filter papers. Single filter sheets were used for the initial separation and then a double layer was used to ensure a final cleaning of the extracts.

Test species used were navy beans *cv.* Envoy, green foxtail and redroot pigweed. Fisher brand petri dishes (100 x15mm) were lined with one sheet of Whatman (90mm) No.1 qualitative filter paper. Twenty-five green foxtail and redroot pigweed seeds and ten navy bean seeds were placed into lined dishes (Burgos and Talbert, 2000). Treatments of 2 ml of fall rye extract, winter triticale extract or winter wheat extract were then applied to the test species. All treatments were replicated four times and arranged in a completely randomized design. Following treatments, plates were covered, wrapped in plastic and put into a dark cabinet at 25°C for six days. Plates were checked at day three to allow for a brief flash of light to stimulate germination in the light sensitive weed species. At the end of the six days, all plates were removed and the total percent

germination was determined based on radical emergence through the seed coat beyond 2mm (Hoagland and Williams, 2004).

3.7 Stastical analysis

The Proc GLM procedure from SAS Institute Inc. (version 9.1) was used for analyzing all data collected from the split-split plot design which required main plot, subplot and subsubplot analysis. The Mixed procedure was used for data from the split plot design which only required main plot and subplot analysis. Bioassay data was also analyzed using The Mixed procedure.

Significance was set at a P value of <0.05 and Scheffe's test was used for determining if treatment means were significantly different from one another. Bartlett's test was used to determine homogeneity among treatment variances.

When data did not conform to the assumptions of ANOVA, either square root, cube root, squared, cubed or cosine transformations were used to produce data that was normally distributed with homogeneity of treatment variances.

4.0 RESULTS AND DISCUSSION

4.1 Weather patterns

Field experiments conducted at Carman, MB and Rosebank, MB in 2006 experienced markedly different weather during their growing seasons compared to field experiments at Winnipeg, MB and Rosebank, MB in 2007.

The spring and summer of 2006 at Carman, MB and Rosebank, MB were characterized by below normal monthly precipitation (Table 4.1). Conversely, in 2007, sites at Winnipeg, MB and Rosebank, MB experienced much greater than average total monthly precipitation during May and following through to July (Table 4.1). Mean monthly air temperatures were less divergent among sites years, however, both years experienced temperatures that were above the long term averages recorded for those areas (Table 4.2).

Table 4.1. Total monthly precipitation for the 2006 and 2007 growing seasons at several southern Manitoba locations

Site location	Year	Apr	May	June	July	Aug
		---mm---				
Carman, MB	**2006[z]**	**34.3**	**28.0**	**50.3**	**26.2**	**37.4**
	Long term avg [y]	**38.4**	**61.1**	**75.5**	**73.5**	**66.8**
Rosebank, MB	**2006[x]**	**20.1**	**48.4**	**43.0**	**16.8**	**39.4**
	Long term avg [w]	**35.5**	**63.3**	**84.4**	**71.2**	**69.9**
Winnipeg, MB	**2007[v]**	**15.8**	**104.4**	**100.8**	**63.8**	**22.6**
	Long term avg [u]	**31.9**	**58.8**	**89.5**	**70.6**	**75.1**
Rosebank, MB	**2007[x]**	**15.4**	**164.6**	**136.8**	**81.4**	**24.0**
	Long term avg [w]	**35.5**	**63.3**	**84.4**	**71.2**	**69.9**

z Source: Environment Canada: Carman U of M
y Source: Environment Canada: 30 year average for 1971-2000 at Graysville
x Source: Environment Canada: Morden
w Source: Environment Canada: 30 year average for 1971-2000 at Morden
v Source: Point Weather Station, University of Manitoba
u Source: Environment Canada: 30 year average for 1971-2000 at Winnipeg Richardson Int'l Airport

Table 4.2. Mean monthly air temperature for the 2006 and 2007 growing seasons at several southern Manitoba locations

Site location	Year	Apr	May	June	July	Aug
		----------	----------	° C	----------	----------
Carman, MB	2006[z]	8.5	12.4	17.9	20.4	18.8
	Long term avg [y]	4.4	12.4	17.2	19.7	18.1
Rosebank, MB	2006[x]	9.0	12.7	19.0	22.0	19.8
	Long term avg [w]	4.7	12.9	17.7	20.1	19.1
Winnipeg, MB	2007[v]	4.8	12.6	18.4	22.1	18.2
	Long term avg [u]	4	12	17	19.5	18.5
Rosebank, MB	2007[x]	4.6	12.7	18.0	21.9	18.1
	Long term avg [w]	4.7	12.9	17.7	20.1	19.1

z Source: Environment Canada: Carman U of M
y Source: Environment Canada: 30 year average for 1971-2000 at Graysville
x Source: Environment Canada: Morden
w Source: Environment Canada: 30 year average for 1971-2000 at Morden
v Source: Point Weather Station, University of Manitoba
u Source: Environment Canada: 30 year average for 1971-2000 at Winnipeg Richardson Int'l Airport

4.2 Soil water content post tillage and prior to seeding

Gravimetric soil water content was measured to determine if rye cover crops deplete soil water reserves. There is concern that cover crops may deplete soil water in the dryland Prairies, though in Manitoba conditions are often too wet for optimum bean establishment. Hence, the question became: Can rye dewater wet soils creating more favorable establishment conditions for dry beans?

In response to this question, it was found that rye does not significantly affect soil water content when there is abundant soil moisture, however, if soil moisture is limited by rainfall; then soil type and texture most likely contribute substantially to the final outcome

At Carman, MB in 2006, the rye cover crop significantly reduced total gravimetric soil water content at the 0-50 cm (Table 4.3) and 0-10 cm soil depths (Table. 4.4) compared to no cover controls. At the other three site-years, no difference in surface (0-10 cm) or subsurface (0-50 cm) soil water content was observed

Table 4.3. Soil water content in response to cover crop and time of initial tillage at 0-50 cm depth

Treatment[z]	Soil water content (g/g)			
	Carman[y] 2006	Rosebank[y] 2006	Winnipeg[x] 2007	Rosebank 2007
Cover crop				
rye	70 b[w]	81 a	231 a	186 a
no rye	92 a	89 a	233 a	191 a
P value	0.006	ns[v]	ns	ns
Time of tillage				
early	85 a	84 a	229 a	182 a
late	77 a	85 a	234 a	195 a
P value	ns	ns	ns	ns
P value				
C*T	ns	ns	ns	ns

z Refer to Table 3.4 for date of tillage, developmental stage and rate of incorporated rye biomass
y Means are presented based on original data. P values are based on cubed transformations.
x Means are presented based on original data. P values are based on Cosine transformations.
w Treatment means within a column followed by the same letter are significantly different (P>0.05)
v ns = not significant

Table 4.4. Soil water content in response to cover crop and time of initial tillage at 0-10 cm depth

Treatment[z]	Soil water content (g/g)			
	Carman[y] 2006	Rosebank[y] 2006	Winnipeg[x] 2007	Rosebank 2007
Cover crop				
rye	36 b[w]	32 a	108 a	161 a
no rye	49 a	39 a	116 a	171 a
P value	0.03	ns[v]	ns	ns
Time of tillage				
early	37 a	37 a	111 a	153 b
late	47 a	34 a	119 a	179 a
P value	ns	ns	ns	0.01
P value				
C*T	ns	ns	ns	ns

z Refer to Table 3.4 for date of tillage, developmental stage and rate of incorporated rye biomass
y Means are presented based on original data. P values are based on cubed transformations.
x Means are presented based on original data. P values are based on Cosine transformations.
w Treatment means within a column followed by the same letter are significantly different (P>0.05)
v ns = not significant

due to the presence of a rye cover crop. These three site-years have similarly heavier soils, predominantly clay. In 2007, spring conditions were wet. Precipitation for May at Rosebank and Winnipeg generally was 104 mm and 164 mm, respectively. Therefore, all plots would have adequate water supply in 2007 while conditions in 2006 were much drier. These findings may suggest that rye's effect on soil water only becomes apparent when rye is grown on lighter soils during drought conditions. Working in Minnesota, De Bruin et al (2005) also observed dramatic differences in cover crop effects due to total precipitation. When spring precipitation was well above normal, the rye cover crop did not significantly affect soil water content. However, when precipitation was well below normal prior to and during their spring and early summer, significantly less soil water to the 30 cm depth were present in plots where rye was grown compared with the control. Soil types were silty loam and clay loam, similar to those at the Carman site.

Considering the initial question, it would appear that rye may not be an effective way to reduce soil water content, although it has been thought to increase water infiltration, improve soil water movement and reduce compaction (Blackshaw, 2008) Rye does, however, use soil water as indicated by its effects at Carman. Some investigations on cover crop water usage have found little difference in soil water content below 15 cm (Ewing et al., 1991) while others have shown significant differences (Utomo et al, 1990). Dissimilarity reported in the literature regarding cover crop water use is thought to reflect climate (year) and soil type differences in spring cover crop management (Odhiambo and Bomke, 2007). Soil type and spring moisture conditions, therefore, should be considered when adopting and managing rye cover crops.

Time of tillage was found to significantly affect soil water content at Rosebank in 2007, whereby higher gravimetric soil water content was measured at the 0-10 cm soil depth in late tillage treatments compared to early tillage treatments (Table 4.4). This may indicate that under high rainfall creating high soil moisture conditions, surface soil drying is improved by early tillage operations. No tillage effects on soil water content were observed at the other sites.

4.3 Influence of rye and time of initial tillage on weed dynamics

A primary objective of this study was to determine the effects of rye, terminated at both early and late developmental stages, on weed population densities within a dry

bean crop. The basic questions were: How well does rye control weeds? How much rye does it take to achieve weed control, and does any weed suppressing effect of a rye cover crop persist beyond the crop emergence period? Results in this section will show that rye did in fact suppress weed growth.

4.3.1 Weed population densities

Rye significantly reduced broadleaved weeds in all site years, while rye suppressed grassy weeds at three of four site years compared with bare soil controls (Table 4.5). Reduction in densities of broadleaved weed species, due to rye, ranged from 44% to 72% (Table 4.5). The dominant broadleaved species present were redroot pigweed (*Amaranthus retroflexus*), lamb's quarters (*Chenopodium album*), wild buckwheat (*Polygonum convolvulus*), smartweed (*Polygonum spp.),* round leaved mallow (*Malva pusilla*) and thyme-leaved spurge (*Chamaesyce serpyllifolia*). Similar accounts of redroot pigweed, lamb's quarters, wild buckwheat and smartweed suppression with rye cover crops were reported previously (Teasdale and Mohler, 2000; Barnes and Putnam, 1983; Baberi and Mazzoncini, 2001; Westgate et al, 2005). No scientific literature on effects of rye on round leaved mallow or thyme leaved spurge could be found.

Significant reductions in densities of grassy weed species due to rye, ranged from 43% to 88% (Table 4.5). Dominant grass weeds present in this study included green foxtail (*Seteria viridis*), wild oat (*Avena fatua*) and barnyard grass (*Echinochloa crusgalli*). Accounts of rye suppressing green foxtail, wild oat and barnyard grass have been also been reported in the literature (Barnes and Putnam, 1983, 1986, 1987; Moonen and Barberi, 2005; Teasdale et al, 2005). Reductions in weed populations observed here were attributed to physical suppression by rye's biomass and chemical suppression through allelopathic compounds.

The effect of initial tillage time was only significant for broadleaf species at one of four site years (Carman, MB in 2006). In this case, lower weed densities were recorded for the late tillage compared with early tillage treatments (Table 4.5). A possible explanation for this observation could be that early tillage treatments stimulated greater germination and subsequent emergence compared to late tillage treatments. This premise is supported with reference to weed emergence periodicity requirements, influenced by

treatment and site year conditions. The dominant broadleaved weed species present at the Carman site were mostly annual species. Most annual weed species are classified as ruderals whereby disturbances necessitate their dominance (M^c^Pherson, 1994). Following a disturbance, these weeds begin emerging early— mid to late May — depending on moisture and temperature (Bullied et al, 2003). Typically, warmer, drier conditions promote germination of summer annuals (Egley, 1986), conditions that were found at Carman in the spring of 2006. Early tillage treatments, therefore, may have stimulated greater germination relative to late treatments as early tilled soils would warm faster than late tilled soils. Late tillage treatments may have remained cooler, longer, and thus germination would be less favorable. All other site years found no significant difference in weed population densities between tillage dates (Table 4.5).

A hypothesis in this study was that the more rye biomass present in spring before bean planting, the greater the weed suppression. Hence, a cover*time interaction was expected to show that better weed control, by rye, would be achieved with greater biomass following late termination. However, no interaction between rye and tillage time was observed for either broadleaved or grassy weeds in this study. This lack of interaction indicates that weed control, by rye, did not improve as rye biomass increased, as was originally hypothesized. These findings differ from those of Teasdale et al (1991), where regression analysis demonstrated a correlation between rye biomass and weed density reductions. Teasdale et al. (1991) reported 15% weed reduction with 800 kg/ha of rye residue, but as rye biomass was increased to 2000 kg/ha and 4000 kg/ha, weed densities reductions increased to 50% and 75%, respectively. Teasdale et al. (1991) attributed this weed suppression by rye, to light extinction and microclimate changes brought on by an increase in the residue layer; rye biomass was positively related to light extinction. Results of the present experiment showed that weed reduction percentages of 45% to 85% occurred at 555 kg/ha to 1570 kg/ha, those rates associated with early termination of the young rye cover.

It has been found that allelopathic root exudates are greatest during rye's early growth and that rye tissue contains higher amounts of these suppressive compounds when the plant is younger. For example, Perez and Ormeneno-Nunez (1991) found high

Table 4.5 Broadleaved and grass weed densities in response to cover crop and time of initial tillage

	Weeds m/^{2}							
	Broadleaved[y]				Grasses[x]			
Treatment[z]	Carman 2006	Rosebank 2006	Winnipeg 2007	Rosebank[w] 2007	Carman 2006	Rosebank 2006	Winnipeg[v] 2007	Rosebank 2007
Cover crop								
rye	93 b[u]	NA[t]	11 b	28 b	358 b	2136 b	19 b	2 b
no rye	336 a	NA	27 a	51 a	481 a	3742 a	50 a	18 a
P value	0.03	NA	0.03	0.04	ns[s]	0.02	0.005	0.02
Time of tillage								
early	249 a	NA	19 a	5 a	444 a	3260 a	36 a	11 a
late	179 b	NA	18 a	6 a	395 a	2617 a	33 a	10 a
P value	0.03	NA	ns	ns	ns	ns	ns	ns
P value								
C* T	ns	NA	ns	ns	ns	ns	ns	ns

z Refer to Table 3.4 for date of termination, developmental stage and rate of incorporated rye biomass
y Main broadleaved species: redroot pigweed, lamb quarters, wild buckwheat, smartweed, round leaved mallow and thyme leaved spurge
x Main grass species : green foxtail, yellow foxtail, wild oat and barnyard grass
w, v, Means are presented based on original data. P values are based on square root transformations
u Treatment means within a column followed by the same letter are significantly different (P>0.05)
t NA = not applicable s ns = not significant

amounts of hydroxamic acids were released from roots of rye cultivars during the period of emergence and the first leaf stage. Burgos et al. (1999) found that total hydroxamic content in tissues of eight rye cultivars increased up to 60 days after planting and declined thereafter, indicating that rye's allelopathic abilities decline with age. Early season competition for light in particular, as well as moisture and nutrients between the growing rye and weeds cannot, however, be discounted as a source of suppression, as living mulches affecting these factors have been documented (Battla et al, 2000; Shilling et al, 1985; Teasdale, 2003).

Hence, results of the present study, where weed suppression was observed with relatively low rye biomass levels suggest that weed suppression by a rye cover crop may more be attributed to competition and chemical suppression before and shortly after incorporation. Therefore, additional rye biomass beyond what is present at the fourth leaf stage may not facilitate greater weed suppression.

The main conclusion that can be drawn from this data are that rye cover crops control a range of summer annual weed species, but more biomass in the soil does not result in greater weed suppression.

4.3.2 Weed biomass

Early season weed densities indicated the effect of rye cover crops on weed emergence. Total accumulated weed biomass, on the other hand, is an indicator of how rye affected weed growth and vigor within the bean crop over the entire growing season. In this study, weed biomass was assessed when dry beans were at full maturity in 2006 and beginning maturity in 2007. Biomass for broadleaved and grassy weeds was measured separately.

4.3.2.1 Broadleaved and grassy weed biomass

Rye was found to significantly reduce total broadleaf weed biomass at harvest, in all three site years where these weeds were present (Table 4.6). Rye lowered total broadleaf weed biomass by 50% at Carman in 2006, 68% at Winnipeg in 2007 and 94% at Rosebank in 2007 compared to the no cover controls. These results indicate that rye not only provided early season control by limiting initial weed populations (Table 4.5),

but that the effects of rye on season-long competitiveness by broadleaved weeds persisted throughout the growing season. This supports the findings of Blackshaw (2008) who observed that winter rye, in the absence of herbicides, reduced total weed biomass from 1725 g/m^2 to 731 g/m^2 and Barnes and Putnam (1983) who found that barnyard grass and redroot pigweed biomass was reduced by 74% and 55%, respectively under rye residues. Both studies attributed this reduction in weed biomass by rye to a combination of physical and allelopathic effects.

In this study, rye's effects on grass species were variable. The presence of a rye cover crop did not significantly affect grass weed biomass at Rosebank in 2006 or Winnipeg in 2007, however, significant effects were observed at Carman in 2006 and Rosebank in 2007 (Table 4.6). In these cases, rye reduced grass biomass by 42% and 65%, respectively. Although rye allelochemicals have been shown to strongly inhibit seedling growth of several dicot species, Barnes and Putnam (1987) found that monocots—grass weeds—were 30% less sensitive to rye's allelochemicals than dicots—broadleaved weeds. This could be one reason why the effects of rye on grass weeds are inconsistent relative to the consistent control observed in broadleaved species.

Tillage date did not significantly affect weed biomass in any site year or for any weed specie. In this study it was thought that soils in early tillage treatments warmed and dried faster relative to late tillage treatments. Although warmer, drier conditions are known to drive germination in summer annuals (Egley, 1986), it would appear that weed vigor, in this study, was unaffected by differential soil temperature or moisture regimes.

Again it was expected that an interaction between rye termination and time of initial tillage would show that greater rye biomass at late termination would result in less total weed biomass. Some previous literature showed that weed biomass was inversely proportional to the amount of cover crop biomass, where more cover crop biomass lessens total weed biomass (Teasdale, 1996, Liebman and Davis, 2000). However, no significant interaction was observed in the present study, again suggesting that rye biomass amount at time of incorporation did not influence weed biomass at harvest. Yenish et al (1995) found that two allelochemicals, BOA (2(3H)-benzoxazonlinone) and DIBOA (2,4-dihydroxy-1,4(2H)-benzoxazin-3-one), persisted up to 168 days in the residues after rye was killed. Since allelochemical release from rye tissues happens

together with residue decomposition, it can perhaps be implied that less rye biomass may have the same relative effect as more rye biomass, provided weed species are sensitive, the rye cultivar has strong chemical presence, and residue decomposition is favorable. It was also interesting to note that although rye did not significantly reduce initial grass weed densities at Carman in 2006, there was a significant reduction in accumulated grass weed biomass indicating that although grass germination was not affected, growth success was. This lends support to the evidence that rye interferes with weed success outside early season competition. It may be interesting at this point to mention a second field study by Perez and Ormemeno-Nunez (1993). They found that a living rye crop, exuding hydroxamic acids through its roots, reduced total accumulated weed biomass by 76% relative to forage oats, a plant with high competitive performance but no hydroxamic acid production. Crop density, spacing and total crop biomass was similar among rye and oats in this study.

The addition of herbicide significantly reduced weed biomass for all weeds in all site years (Table 4.6). In addition, a significant in-crop herbicide by rye cover crop interaction was observed. When herbicides were not used, rye reduced broadleaf weed biomass below that of no cover controls by 58%, 64% and 80% at Carman, Winnipeg and Rosebank. When in-crop herbicides were used, rye resulted in less accumulated broadleaf weed biomass compared to controls by 23%, 35% and 24% at Carman, Winnipeg and Rosebank, respectively. Despite this interaction, it appeared that in order for maximal reductions in broadleaf weed biomass, a combination of rye and herbicides is best. There were no similar interactions between rye and herbicide on grass species (Table 4.6). This gives further indication of rye's shortcomings for achieving total grass weed control.

Results of this study indicate that rye limits accumulated weed biomass relative to no cover controls and that broadleaved weeds were more sensitive to the effects of rye than grass weeds. Further, it was observed that rye's ability to reduce weed growth and subsequent weed biomass was not improved when larger quantities of rye biomass were added to the system. Similar to results with weed population density, time of tillage did not affect weed growth response and weed biomass.

Table 4.6. Accumulated broadleaved and grass weed biomass at harvest in response to cover crop, time of initial tillage and in-crop herbicide application

Treatment[z]	----------Weeds kg/ha----------							
	Broadleaved[y]				Grasses[x]			
	Carman 2006	Rosebank 2006	Winnipeg[w] 2007	Rosebank[v] 2007	Carman[u] 2006	Rosebank[t] 2006	Winnipeg[s] 2007	Rosebank[r] 2007
Cover crop								
rye	578 b[q]	NA[p]	317 b	36 b	416 b	1034 a	203 a	7 b
no rye	1134 a	NA	989 a	613 a	716 a	1648 a	292 a	36 a
P value	<0.0001	NA	0.01	0.0006	0.03	ns[o]	ns	0.04
Time of tillage								
early	820 a	NA	766 a	423 a	586 a	1290 a	151 a	27 a
late	742 a	NA	606 a	227 a	546 a	1392 a	343 a	16 a
P value	ns	NA	ns	ns	ns	ns	ns	ns
Herbicide								
control	1424 a	NA	1242 a	599 a	924 a	2678 a	457 a	41 a
applied	158 b	NA	118 b	51 b	206 b	5 b	37 b	2 b
P value	<0.0001	NA	<0.0001	0.0007	<0.0001	<0.0001	0.0003	0.007
P value								
C* T	ns	NA	ns	ns	ns	ns	ns	ns
C*H	0.002	NA	0.04	0.01	ns	ns	ns	ns
T*H	0.03	NA	ns	ns	ns	ns	ns	ns
C*T*H	ns	NA	ns	ns	ns	ns	ns	ns

z Refer to Table 3.4 for date of tillage, developmental stage and rate of incorporated rye biomass
y Main broadleaved species present: redroot pigweed, lamb quarters, wild buckwheat, smartweed, round mallow and thyme leaved spurge
x Main grass species present: green foxtail, wild oat and barnyard grass
w, v ,u ,t, s ,r Means are presented based on original data. P values are based on transformations of original data
q Treatment means within a column followed by the same letter are significantly different (P>0.05)
p NA = not applicable; o ns = not significant

4.3.2.2 Total weed biomass

Total weed biomass was measured to determine overall weed competitiveness within the dry bean crop. Rye significantly reduced total weed biomass compared to the no cover control at Carman (2006), Winnipeg (2007) and Rosebank (2007) (Table 4.7). At Carman in 2006, total weed biomass accounted for 18% and 31% of the total biomass harvested from rye and no rye treatments, respectively (Table 4.7). At the Winnipeg site total weed biomass accounted for 22% and 35% of the total harvested biomass from rye and no rye

z Refer to Table 3.4 for date of tillage, developmental stage and rate of incorporated rye biomass

Table 4.7 Total accumulated weed biomass in response to cover crop, time of initial tillage and in-crop herbicide application

	Total Weed Biomass (kg/ha)			
Treatment[z]	Carman[y] 2006	Rosebank 2006	Winnipeg 2007	Rosebank[y] 2007
Cover crop				
rye	964 b[x]	1034 a	575 b	43 b
no rye	1988 a	1648 a	1279 a	642 a
P value	0.0008	ns[w]	0.003	0.0007
Time of tillage				
early	1688 a	1290 a	971 a	442 a
late	1262 a	1392 a	924 a	242 a
P value	ns	ns	ns	ns
Herbicide				
control	2624 a	2678 a	1698 a	639 a
applied	314 b	5 b	156 b	45 b
P value	<0.0001	<0.0001	0.003	0.0003
C*T	ns	ns	ns	ns
C*H	0.03	ns	0.02	0.01
T*H	ns	ns	ns	ns
C*T*H	ns	ns	ns	ns

y Means are presented based on original data. P values are based on square root transformations
x Treatment means within a column followed by the same letter are significantly different (P>0.05)
w ns = not significant

treatments, respectively, and Rosebank weed biomass in 2007 was found to account for <1% and 11% of the total accumulated biomass removed from rye and no rye treatments, respectively. These results indicate that in three of four site years, the presence of rye

reduced weed competitiveness' in the bean crop such that dry bean biomass production increased by 10-13% compared to controls.

Similar to results on separated broadleaved and grass weed biomass, tillage date did not significantly affect total weed biomass in any site year or for any weed specie.

In-crop herbicide applications significantly decreased total accumulated weed biomass at all four site-years (Table 4.7). A significant interaction was observed at Carman in 2006 and Winnipeg and Rosebank, in 2007 between rye and in-crop herbicides. At these sites this interaction showed that when in-crop herbicides were applied total weed biomass was similar, however, when in-crop herbicides were absent, rye reduced total weed biomass compared to the control treatment by 52%, 60% and 92% at Carman, Winnipeg and Rosebank, respectively.

The results from this study found that when rye is incorporated into dry bean production, its presence can limit weed growth such that dry bean biomass production is increased beyond that produced when rye is not present. Additionally, in the absence of herbicides, rye limits weed growth such that, compared to controls, 52%-92% less weed biomass accumulates and is present within the crop at the end of the growing season.

4.4 Dry bean crop production

Utilization of rye cover crops in dry bean production will only be adopted by farmers if the addition of rye brings about positive influence or change. Therefore, determining how dry beans respond to a rye cover crop was the second primary objective of this study. This objective was achieved by measuring bean plant establishment, development, growth, and seed yield.

4.4.1 Dry bean plant population density

The effect of rye cover crop management on dry bean plant population density, at full emergence, was a necessary measure to determine if rye had negatively affected dry bean establishment or if delayed tillage had led to suboptimal conditions for bean establishment. Visual observations comparing the time of tillage treatment clearly showed that bean populations were sparser in late tillage treatments relative to early treatments (Fig. 4.1). Less evident were any visual effects of rye on bean establishment (Fig 4.2).

Over all site-years, plant population densities ranged between 23 plants/m^2 and 42 plants/m^2 (Table 4.8). The recommended target plant population for dry edible beans is 35-45 plants/m^2 (SPG, 2000). The slightly lower than optimum plant population densities in these experiments may be attributed to low end seeding rates. The rates used in this experiment were ~90kg/ha. According to SPG (2000), navy bean seeding rates should be between 90 kg/ha to 112 kg/ha.

Fig 4.1 Bean populations in early tillage (left) and late tillage (right) treatments at Rosebank, 2006

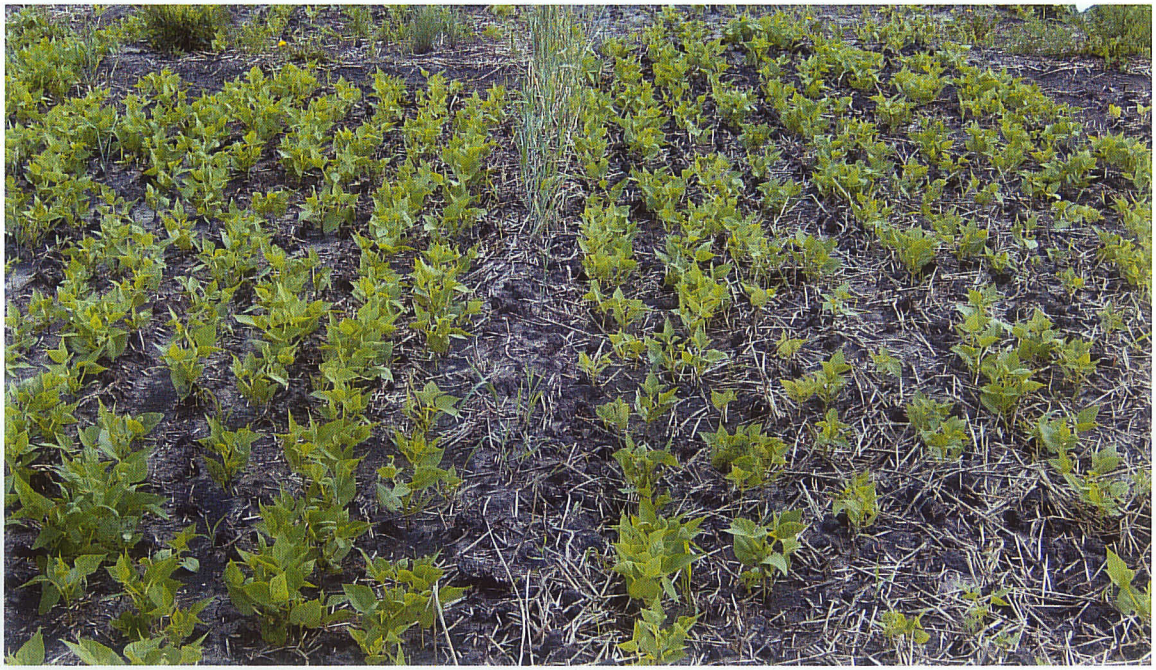

Fig 4.2 Bean populations in no cover controls (left) and rye (right) treatments at Winnipeg, 2007

Rye was found to significantly reduce dry bean plant density at Carman in 2006 compared to control treatments. No significant differences between rye and the control were observed for dry bean plant density at the other three site-years (Table 4.8). The negative effect of rye at Carman in 2006 may have been the result of low precipitation combined with rye's significant affect on soil moisture (Table 4.1, 4.3. 4.4). Dry seedbed conditions during the subsequent germination and emergence period for the crop would likely reduce bean establishment.

Rye did not affect soil moisture at Rosebank, 2006, Winnipeg, 2007 and Rosebank, 2007 and at these sites, plant population density was not affected by rye (Table 4.3, 4.4, 4.8). Blackshaw (2008) and Liebman and Davis (2000) observed no negative effect of winter rye on dry bean plant population density. The lack of negative rye effects in three of four site years suggests that the physical and chemical suppressive nature of rye was not acting as a deterrent on dry bean establishment.

In contrast to the findings on weed population densities, late tillage was shown to significantly affect dry bean population density, in three of four site years (Table 4.8). Late tillage at Carman and Rosebank in 2006 resulted in a 20% and 33% decrease in plant population density relative to early tillage treatments, respectively. Late tillage treatments at Rosebank in 2007 showed a 15% reduction in bean density. Tillage time had no significant effect on plant population density at Winnipeg in 2007 (Table 4.8). The lower densities resulting from delaying tillage may be due to poor seed germination resulting from cooler soils in late tillage, relative to earlier tillage treatments. While soil temperature data was not measured here, the link between early tillage and soil temperature is well documented (Mahli and O'Sullivan, 1990). Others have observed that low seedbed temperatures can be detrimental to dry bean establishment (Balasubramanian et al, 2004). In addition, the clay soils at Rosebank were somewhat compacted and hard to till. This resulted in large, hard clumps, or clods, in the seedbed (Fig 4.3, 4.4). Early tillage had encountered similar conditions, however, longer exposure to environmental conditions allowed them to loosen and break apart prior to and during seeding. In 2007, early tillage treatments received an extra tillage pass 7 to 10 days after the initial pass, thus further smoothing down the seed bed. Poor seed/soil contact in late tillage treatments at Rosebank may have contributed to poor bean seed germination as seedbed conditions were poor (Fig 4.3, 4.4). Buttery et al (1998) found that root growth of common bean was severely restricted by hard, dry, compacted soils.

These findings suggest that early tillage treatments allow for improvement of suboptimal seedbed conditions. If soil conditions are cool, wet, or too rough, early tillage—7 to 10 days prior to seeding—improves dry bean establishment and overall plant population density. High moisture clay soils may be further improved by an additional pass immediately prior to seeding.

Fig 4.3 Clumpy seedbed conditions of late tillage treatments at Rosebank 2007

Fig 4.4 Poor seedbed conditions in late tillage treatments at Rosebank 2006. Note: uncovered bean seeds in center of picture

Table 4.8 Dry bean plant density in response to cover crop and time of initial tillage

Treatment[z]	Plants/m^2			
	Carman 2006	Rosebank 2006	Winnipeg 2007	Rosebank 2007
Cover crop				
rye	28 b[y]	29 a	24 a	35 a
no rye	42 a	32 a	25 a	35 a
P value	0.007	ns[x]	ns	ns
Time of tillage				
early	38 a	36 a	26 a	38 a
late	31 b	24 b	23 a	32 b
P value	0.03	0.02	ns	0.005
P value				
C*T	ns	ns	ns	ns

z Refer to Table 3.4 for date of tillage, rye developmental stage and rate of incorporated biomass
y Treatment means within a column followed by the same letter are significantly different (P>0.05)
x ns = not significant

4.4.2 Early dry bean growth and development

Early bean development, measured until full seedling emergence, was monitored to determine if rye treatments or time of initial tillage had an affect on the speed of bean leaf appearance.

Rye only affected bean development at one of the four site-years. At Carman in 2006, rye significantly slowed bean development, beginning on the second recorded date, until full emergence (Fig 4.5). Throughout the eleven day measurement period, the control treatment successfully completed each trifoliate unfurling about three days ahead of the rye treatments. Blackshaw (2008) also observed a three to five day delay in dry bean development following a winter rye cover crop which he attributed to cooler soil temperatures resulting from rye's biomass. Lower levels of water availability at the 0-10 cm depth (P<0.05), by rye, prior to seeding at Carman in 2006 (Table 4.4), combined with low precipitation (Table 4.1, 4.2) may have contributed to this delay in development. No difference in bean development was observed at any other site (Fig 4.6, 4.7, 4.8), and at those sites, rye had not affected seedbed moisture (Table 4.3, 4.4).

Comparing early tillage to late tillage treatments revealed that bean development was slower for the late tillage treatment in all four site years. Delayed bean development

with delayed tillage was observed for both measurement times at Winnipeg and Rosebank in 2007 (Fig 4.7, 4.8). In 2006, effects of late tillage were observed during later measurement times at both sites (Fig 4.1, 4.2). A possible reason for more rapid bean development with earlier tillage may be improved seedbed conditions resulting from faster soil warming and drying. Soil disturbance can lead to improved soil aeration, increased soil temperature and reduced soil moisture (Mahli and O'Sullivan, 1990). Earlier tillage would allow for improved drying and warming of the seedbed, particularly in the clay soils at Rosebank. Therefore, late tillage treatments most likely resulted in soils remaining cooler, as they were exposed to warming air temperatures for a shorter period, relative to earlier termination treatments. Balasubramanian et al (2004) found that cooler seedbed temperatures delayed dry bean emergence.

These results indicate that provided seedbed moisture conditions have not been compromised, rye cover crops do not negatively affect dry bean plant development. Similar to dry bean plant population density, this result may indicate that neither physical, nor allelopathic mechanisms attributed to rye are interfering with dry bean development.

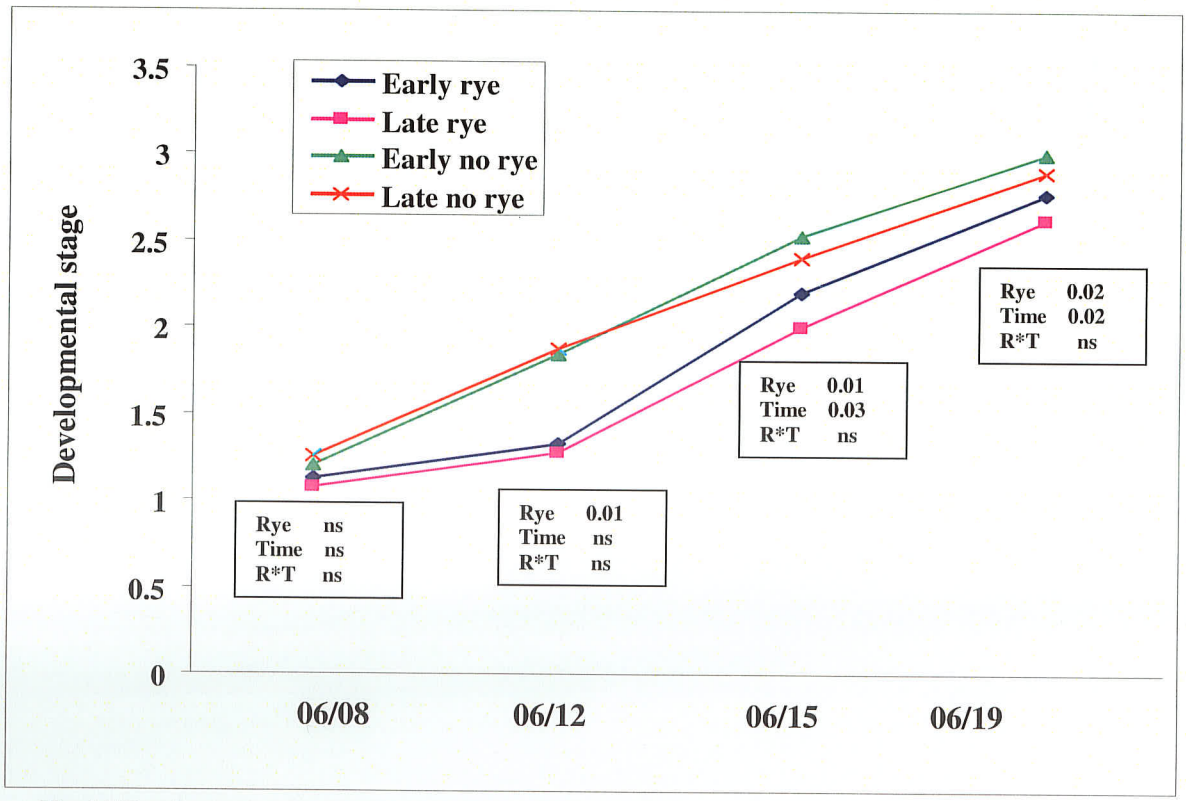

Fig 4.5 Dry bean development at Carman, 2006 as influenced by cover crop and tillage time
Developmental stage: 1 = first trifoliate; 2 = second trifoliate; 3 = third trifoliate

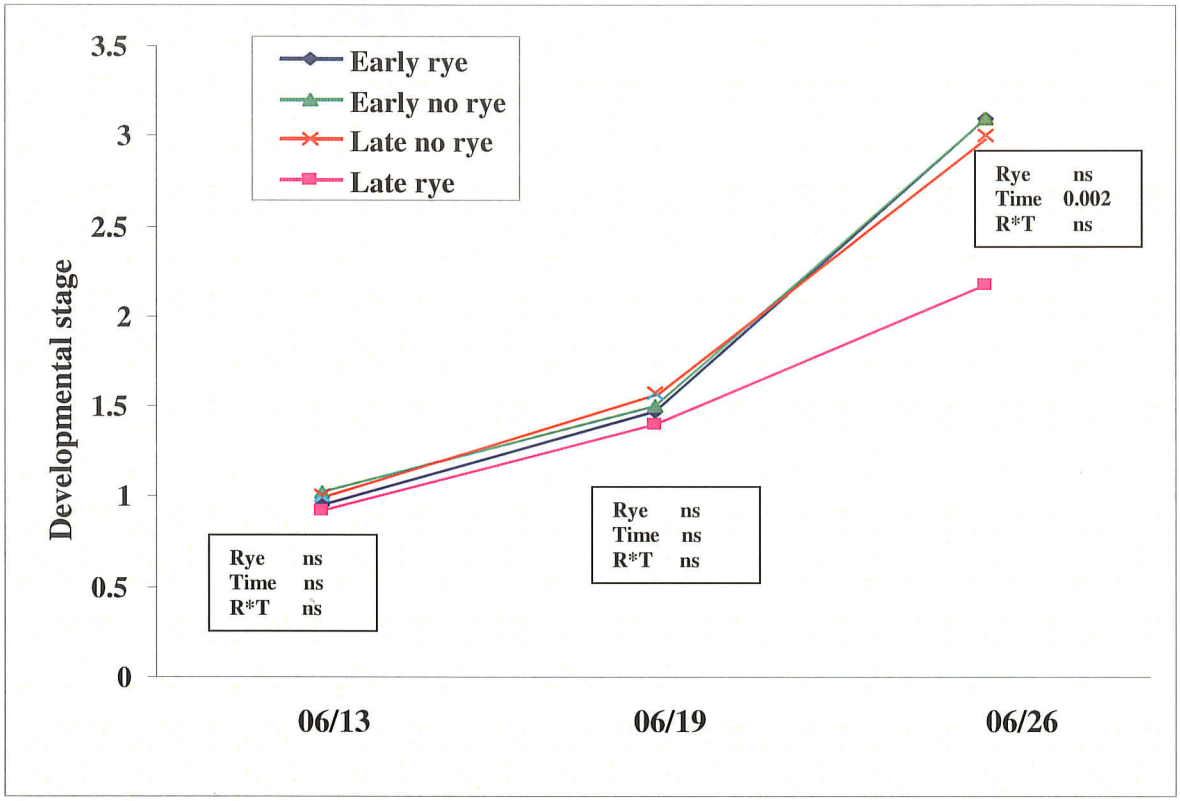

Fig 4.6 Dry bean development at Rosebank, 2006 as influenced by cover crop and tillage time
Developmental stage: 1 = first trifoliate; 2 = second trifoliate; 3 = third trifoliate

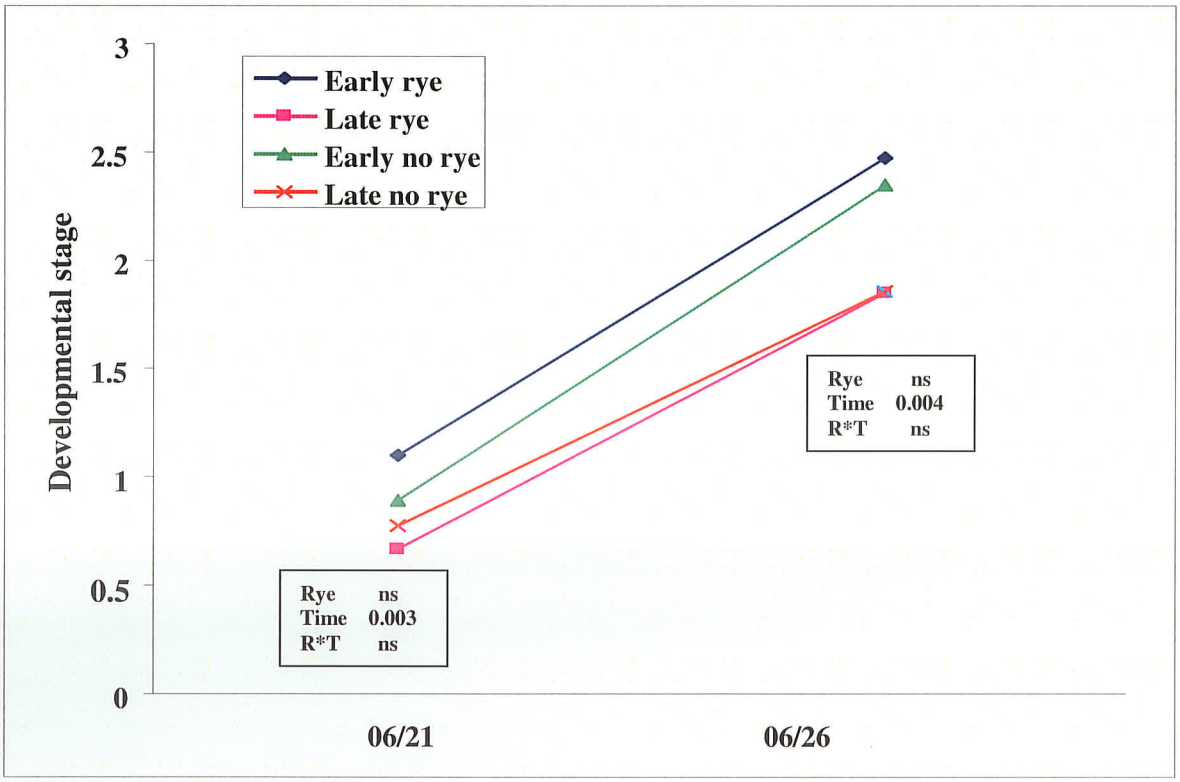

Fig 4.7 Dry bean development at Winnipeg, 2007 as influenced by cover crop and tillage time
Developmental stage: 1 = first trifoliate; 2 = second trifoliate; 3 = third trifoliate

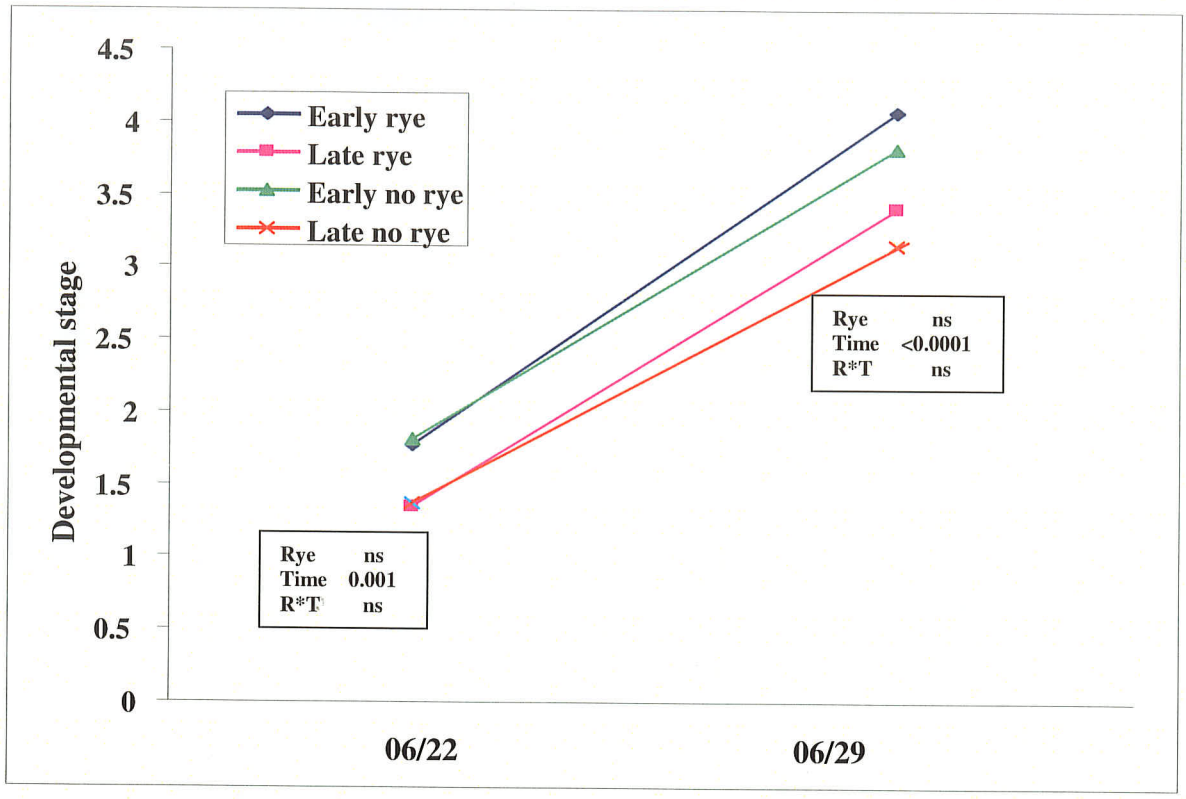

Fig 4.8 Dry bean development at Rosebank, 2007 as influenced by cover crop and tillage time
Developmental stage: 1 = first trifoliate; 2 = second trifoliate; 3 = third trifoliate

4.4.3 Dry bean plant height

Dry bean plant height, measured from the base of the plant to the top of the apical flower, determined whether any negative treatment effects due to rye or time of initial tillage lasted beyond early season bean development. Similar to bean heights measured in this study, reported heights for bush type white pea bean in narrow row production range anywhere from 30 to 55 cm depending on environmental conditions (MPGA, 2007).

Rye reduced ($P<0.05$) dry bean plant height in 2006 at Carman, MB (Table 4.9), an average of 9 cm. No significant effect of rye on bean height was observed at any other site-year (Table 4.9). The negative effect of rye on bean plant height at Carman in 2006 was attributed to significant water use by the rye (Table 4.3, 4.4) combined with low precipitation and high summer temperatures (Table 4.1, 4.2). Plants grow tall when there is adequate moisture, temperatures are not extreme and nutrients are not limiting (Taiz and Zeiger, 2002). The observed delay in early plant development at Carman in 2006,

where plants developed at a slower rate following rye compared to the no cover controls (Fig 4.5), supports why differences in height, at flowering, were observed.

Late tillage resulted in a significant reduction in bean height, compared to early tillage, at Carman in 2006 and Rosebank in 2006 and 2007 (Table 4.9). These reductions in mid season height are most likely prolonged effects of the delayed early growth and development observed at these sites (Fig 4.5, 4.6, 4.7). As previously mentioned (sections 4.4.1, 4.4.2) late tillage treatments most likely had poor seedbed conditions and cooler soils relative to early tillage treatments. Williams et al (2000) attributed reduced soybean early growth and mid season canopy development (based on plant height and width), to soils that were slow to warm.

Herbicide injury resulted in significantly shorter plants in all site years (Table 4.9). Plants responded to herbicide with a 10-15% decrease in height. Plant height is very important for white bean growers using solid seeded production systems since shorter plants are more prone to seed shatter and yield loss when combining (Sikkema et al., 2004). In addition, a significant in-crop herbicide by rye cover crop interaction was observed at Carman, 2006 and Rosebank, 2006. The addition of herbicides in the rye cover crop treatment caused a 1% decrease in height at Carman and Rosebank, whereas the addition of herbicides in the no cover crop control treatment caused a 10% and 7% decrease in height at Carman and Rosebank, respectively. A possible explanation for these findings may be herbicide interception by rye residues. Herbicide interception would be a concern if weed populations were competitive, however, being that rye had significantly reduced initial weed densities and furthermore, total weed biomass at harvest, it would appear that the residues acted as a safeguard to the bean crop and minimized crop injury. Growth reductions are common crop injury symptoms from the in-crop herbicides bentazon and fomesafen use in dry beans (Sikkema et al., 2004). No significant in-crop herbicide by rye cover crop interaction was observed at Winnipeg and Rosebank in 2007. A possible explanation for this may be greater rye residue decomposition, resulting in less surface biomass at the time of herbicide application, due to the high heat and moisture observed at those sites in 2007 compared to 2006 (Table 4.1, 4.2). Heat and moisture placed on the residues favor more rapid decomposition (MacDonald et al, 1995).

4.4.4 Dry bean biomass

Dry bean biomass production in response to rye cover crop treatments varied (Table 4.10). At some site-years there was no significant difference in biomass production compared to controls yet at other sites dry beans responded to rye by producing less total biomass. Time of initial tillage continued to show that late tillage treatments reduced bean growth (Table 4.10).

Table 4.9 Dry bean plant height at flowering in response to cover crop, time of initial tillage and in-crop herbicide application

	Height (cm)[y]			
Treatment[z]	Carman 2006	Rosebank 2006	Winnipeg 2007	Rosebank 2007
Cover crop				
rye	40 b[x]	29 a	37 a	51 a
no rye	51 a	32 a	36 a	51 a
P value	<0.001	ns	ns[w]	ns
Time of tillage				
early	48 a	32 a	37 a	54 a
late	43 b	28 b	36 a	47 b
P value	0.007	0.008	ns	<0.0001
Herbicide				
control	48 a	32 a	38 a	53 a
applied	44 b	28 b	35 b	47 b
P value	0.01	0.008	0.003	<0.001
P value				
C*T	0.03	ns	ns	0.0002
C*H	0.03	0.03	ns	ns
T*H	ns	ns	ns	ns
C*T*H	ns	ns	ns	ns

z Refer to Table 3.4 for date of termination, developmental stage and rate of incorporated rye biomass
y plant height measured from base of plant to the top of the apical flower
x Treatment means within a column followed by the same letter are not significantly different (P>0.05)
w ns = not significant

Rye had no significant effect on dry bean biomass production at Carman and Rosebank in 2006 (Table 4.10). However, at both 2007 sites, rye significantly reduced dry bean biomass production compared to the non-rye control (Table 4.10).

Early tillage treatments resulted in greater (P<0.05) dry bean biomass production compared to late tillage at three of four site-years (Table 4.10). Low dry bean biomass production in delayed tillage treatments is probably the result of delayed emergence,

lower plant population densities and shorter stature plants as indicated by height differences.

Table 4.10 Accumulated dry bean biomass in response to cover crop, time of initial tillage and in-crop herbicide application

Treatment[z]	Dry bean biomass (kg/ha)			
	Carman[y] 2006	Rosebank[x] 2006	Winnipeg 2007	Rosebank 2007
Cover crop				
rye	4286 a[w]	1758 a	2046 b	4636 b
no rye	4466 a	1576 a	2456 a	5111 a
P value	ns[v]	ns	0.005	0.03
Time of tillage				
early	3938 a	1978 a	2501 a	5428 a
late	3818 a	1358 b	2000 b	4319 b
P value	ns	0.01	0.001	<0.0001
Herbicide				
control	2254 b	556 b	1816 a	4951 a
applied	5498 a	2779 a	1686 b	4797 a
P value	<0.0001	<0.0001	<0.0001	ns
***P* value**				
C*T	ns	ns	ns	ns
C*H	ns	ns	ns	ns
T*H	ns	ns	ns	ns
C*T*H	ns	ns	ns	ns

z Refer to Table 3.4 for date of termination, developmental stage and rate of incorporated rye biomass
y, x Means are presented based on original data. P values based on square root transformations
w Treatment means within a column followed by the same letter are significantly different (P>0.05)
v ns = not significant

Addition of in-crop herbicides significantly increased biomass production at Carman and Rosebank in 2006 (Table 4.10). Surprisingly, in-crop herbicide use led to a significant decrease in dry bean biomass production at Winnipeg (Table 4.10). In-crop herbicide biomass production and control treatment biomass production did not significantly differ at Rosebank in 2007 (Table 4.10). Carman and Rosebank sites in 2006 had very high weed densities (Table 4.5); therefore, herbicide use probably benefited these crops by alleviating weed competition for nutrients, moisture and light, thus increasing biomass production. However, in 2007 weed densities were comparatively

lower at Winnipeg and Rosebank (Table 4.5) in which case herbicides may have resulted in unnecessary crop injury.

4.4.5 Dry bean yield

Some previous reports show that a rye cover crop can positively influence bean production systems such that yields are found to exceed those of non cover cropped systems (Blackshaw, 2008; Williams et al, 2000). Results from the present experiment showed that a rye cover crop before dry bean production can result in lower, higher or similar yields. Additionally this study found that early tillage of soils leads to an improvement in yield over late tillage.

Average navy bean yields for Manitoba from 2005 to 2007 were 1500 - 1900 kg/ha (Yield Manitoba, 2008). In the present study, dry bean yield response to rye cover crops was mostly positive. The highest reported yields for all site years was at Rosebank in 2007 where main plots produced 2914 kg/ha and 3024 kg/ha for rye and no rye controls respectively (Table 4.11). In 2006, Rosebank yields were well below all other site- year for both main plot treatments with 422 kg/ha in rye treatments and 455 kg/ha in no cover treatments (Table 4.11). Although extreme yields demarcate these two site-years, no significant differences in yield between rye and no cover controls were observed (Table 4.11). In regards to the low yields at Rosebank in 2006, observations of the area surrounding the plots found large populations of kochia and foxtail barley, indicating that these soils may have had excess salts. However, soil test analysis revealed very low amounts of soil salts (0.25-0.35 mmhos/cm) existed at this site in 2006. Consistency among low plant population densities, height and biomass for dry beans at this site help explain why yield was also affected, however, the cause of this poor crop production could not be determined based on the data available.

Rye significantly reduced dry bean yield at Carman in 2006 (Table 4.11). This yield loss is consistent with rye's affects on growth and development parameters, except total biomass, measured for dry beans at Carman in 2006, beginning with reduced plant population density, delayed emergence and development, and less vertical growth compared to no cover controls. Significant water use by the cover crop (Table 4.3, 4.4)

prior to seeding is most likely the main cause of these effects on growth and yield. Although there was a yield loss attributed to the cover crop at Carman in 2006, the dry bean crop still produced 1428 kg/ha; comparable to those reported by MASC. Results of dry bean yield from the Winnipeg site in 2007 show that rye treatments significantly increased yield by 17% compared to no cover controls (Table 4.11). Protein content (%N) of harvested bean seed from rye treatments at Winnipeg, although not statistically analyzed, were found to be similar to controls, indicating that the higher yield did not arise as a result of protein dilution. Actual nitrogen content for sampled bean seeds was 4.2% and 4.4% for rye and control treatments, respectively.

Dry beans require a good water supply throughout their growth (SPG, 2000). Water stress during flowering and pod filling result in poor seed yield and seed weight (Singh, 1995). It has been suggested that when rye cover crops lead to improvement in dry bean yield that these results are the product of improved water infiltration prior to termination and water conservation from the residues extending through the growing season (Blackshaw, 2008). Considering this, it is possible that the rye cover crop at Winnipeg in 2007 led to better water infiltration prior to termination, as this site experienced high precipitation events prior to seeding (Table 4.1). Following this, the biomass incorporated into the soil may have helped conserve soil moisture throughout the drier summer months such that the bean crop was not experiencing water stress at pod filling, resulting in higher yields relative to controls. Controlled soil drying at pod filling, a result of water conservation by rye, can also make better use of pre-stored carbon reserves and enhance harvest index and water use efficiency for yield (Boutraa and Sanders, 2001). In addition, weed suppression by rye, observed in these treatments, may also have contributed to an improvement in crop performance as there was less competition for water and nutrients. Additionally, a significant interaction at Winnipeg in 2007 was observed between the rye cover crop and time of initial tillage (Table 4.11). This interaction showed that early tillage of a rye cover crop produced yields that were 32% higher than late tillage, however, early tillage in the no cover controls only improved yield by 10% relative to late tillage. This further supports the suggestion that a rye cover crop, terminated early, is beneficial to dry bean production.

Early tillage treatments resulted in significantly higher yields compared to late tillage treatments at three of four site years (Table 4.11). Seed yield in dry bean can be compromised due to low temperatures when planted into suboptimal seedbed temperatures in early spring (Balasubrananian et al, 2004). This is the most probable cause of lower yields following late tillage treatments.

Table 4.11 Dry bean yield response to cover crop, time of initial tillage and in-crop herbicide application

	Dry bean yield (kg/ha)			
Treatment[z]	**Carman 2006**	**Rosebank[y] 2006**	**Winnipeg 2007**	**Rosebank 2007**
Cover crop				
rye	1428 b[x]	422 a	1285 a	2914 a
no rye	2659 a	455 a	1061 b	3024 a
P value	0.012	ns[w]	0.002	ns
Time of tillage				
early	1700 a	500 a	1355 a	3219 a
late	1500 a	375 b	991 b	2719 b
P value	ns	0.002	<0.0001	0.0009
Herbicide				
control	738 b	86.5 b	983 b	2992 a
applied	2462 a	785 a	1364 a	2946 a
P value	<0.0001	<0.0001	<0.0001	ns
P value				
C*T	ns	ns	0.04	ns
C*H	ns	ns	ns	ns
T*H	0.02	ns	ns	ns
C*T*H	ns	ns	ns	ns

z Refer to Table 3.4 for date of termination, developmental stage and rate of incorporated rye biomass
y Means are presented based on original data. P values are based on square root transformations.
x Treatment means within a column followed by the same letter are significantly different (P>0.05)
w ns = not significant

Inclusion of in-crop herbicides significantly improved yield at Carman and Rosebank in 2006 (Table 4.11), where weed pressure was highest (Table 4.5). There was no significant difference in yield when herbicides were applied compared to controls at Rosebank in 2007. Weed pressure was lower at both sites in 2007 (Table 4.5). Therefore, herbicides may have led to crop injury as opposed to weed control. A significant interaction was observed at Carman in 2006 between time of initial tillage and in-crop herbicides. This interaction showed that in the absence of in-crop herbicides, delayed

tillage treatments produced yields 11% above those of early tillage treatments, however, once in-crop herbicides were added, early tillage treatment yields exceeded late tillage by 22%. Carman in 2006 was the one exception where delayed tillage resulted in a significant reduction in initial broadleaved weed densities (Table 4.5). Therefore, less weed competition would have existed in the late treatments compared to early treatments, which could explain that in the absence of in-crop herbicides, yields were higher in late treatments. Although, no significant difference in yield was found for time of initial tillage as a main effect, this interaction showed that when weed competition was removed through the addition of in-crop herbicides, early tillage, unlike delayed tillage, had created conditions such that improved bean productivity and thus, increased yield.

Results of this study indicate that rye cover crops can have varying affects on dry bean. Sometimes, including a rye cover crop prior to dry bean can limit yield and, at other times, it can improve yield. These discrepancies are most likely attributable to differences in environmental conditions and soil types. In a hot dry year, lighter textured soil may be at a disadvantage following rye compared to a year when moisture is not limiting. However, if early spring moisture is abundant or even in excess, rye cover crops may help to improve soil water distribution and then conserve it; resulting in a benefit for the bean crop.

4.4.6 Dry bean harvest index

Harvest index was a useful measure for determining how well the bean plants were able to partition resources into seed production. Harvest index (HI) for dry bean in non water stressed conditions were reported by Muñoz-Perea et al (2007) to range from 0.35-0.45 and by Clark and Carpenter (2002) to range from 0.4-0.55.

Rye significantly reduced harvest index at Carman in 2006 compared to the no cover control (Table 4.12). Although bean biomass production was unaffected by rye compared to controls at Carman (Table 4.10), beans in the control treatment produced a greater ($P<0.05$) harvest index of 0.65 compared to 0.35 observed in the rye treatment (Table 4.12), indicating beans following rye were less able to partition energy to seed production. Reduced harvest index in common bean often accompanies moderate water stress (Foster et al, 1995; Boutraa and Sanders, 2001). Therefore, significant water use,

by rye, observed at Carman prior to bean seeding is the suspected cause of this effect (Table 4.3, 4.4). No significant effect, of rye, on harvest index was observed at Rosebank in 2006 (Table 4.12). At this site-year harvest indices were comparatively low relative to the other three site-years with HI values of 0.23 and 0.28 for rye and the no cover controls, respectively. The low HI values at Rosebank in 2006 found in both rye and the no cover control treatments could be an indication that water stress, possibly the result of high temperatures and low precipitation (Table 4.1, 4.2), was affecting the entire crop. No significant difference between the rye treatment and the control were observed for harvest index at Rosebank in 2007. Rye significantly increased HI at Winnipeg in 2007 compared to the control with HI values of 0.63 and 0.43 for rye and the no cover control, respectively (Table 4.12). This suggests that beans grown following the rye cover crop at the Winnipeg site, were using assimilates for seed production more so than biomass production.

Table 4.12 Dry bean harvest index in response to mainplot treatments

	Harvest Index			
Treatment[z]	**Carman 2006**	**Rosebank 2006**	**Winnipeg 2007**	**Rosebank 2007**
Cover crop				
rye	**0.35 b[y]**	**0.23 a**	**0.67 a**	**0.65 a**
no rye	**0.65 a**	**0.28 a**	**0.45 b**	**0.60 a**
***P* value**	**0.03**	**ns**	**0.004**	**ns**

z Refer to Table 3.4 for date of termination, developmental stage and rate of incorporated rye biomass
y Treatment means within a column followed by the same letter are significantly different (P>0.05)

4.4.7 Dry bean seed weight

Harvested dry bean seed weight was measured to ensure that any yield increase attributed to the rye cover crop had not resulted in compromised seed quality. One thousand seed weight for navy bean should be 170g-210g (SPG, 2000).

Rye significantly increased individual seed weight compared to controls in harvested bean seeds at Winnipeg in 2007 (Table 4.13). This indicates that seed quality was not compromised but improved due to the presence of the cover crop before bean production. In addition, the combination of higher (P<0.05) yield, harvest index and 1000 seed weight for beans following rye at Winnipeg indicate that plants were producing larger seeds and more seeds per plant compared to plants not grown following

rye (Tables 4.11, 4.12, 4.13). No significant differences were observed in seed weight when mainplot treatments at Rosebank in 2007 were compared.

Time of initial tillage showed no significant difference between early and delayed tillage treatments at Winnipeg or Rosebank in 2007 (Table 4.13). This may indicate that bean plants grown under delayed tillage conditions, produce seeds of similar weight compared to early tillage treatments, however, they produce fewer seeds as indicated by the significantly lower yields observed in delayed tillage treatments (Table 4.11).

In-crop herbicide applications at Winnipeg significantly increased seed weight compared to the control and most likely the result of reduced weed competition for factors required for assimilate production. A significant interaction between time of initial tillage and in-crop herbicides was observed at Winnipeg in 2007 (Table 4.13).

The results of this study indicate when higher yields are produced by a bean crop following rye; bean seed quality as indicated by seed weight, is also improved.

Table 4.13 Harvested dry bean seed weight in response to cover crop, time of initial tillage and in-crop herbicide application

	1000 seed weight (g)	
Treatment[z]	**Winnipeg 2007**	**Rosebank 2007**
Cover crop		
rye	**172 a[y]**	**186 a**
no rye	**159 b**	**185 a**
***P* value**	**0.001**	**ns**
Time of tillage		
early	**166 a**	**186 a**
late	**164 a**	**184 a**
***P* value**	**ns**	**ns**
Herbicide		
control	**157 b**	**184 a**
applied	**174 a**	**188 a**
***P* value**	**0.0001**	**ns**
***P* value**		
C*T	**ns**	**ns**
C*H	**ns**	**ns**
T*H	**0.01**	**ns**
C*T*H	**ns**	**ns**

z Refer to Table 3.4 for date of tillage, rye developmental stage and rate of incorporated biomass
y Treatment means within a column followed by the same letter are significantly different P(>0.05)
x ns = not significant

4.5 Bioassays with crude aqueous extracts of fall rye

Rye tissue extracts, from greenhouse grown plants, were found to significantly reduce germination in redroot pigweed by 37% and green foxtail by 21% compared to water controls (Table 4.14). Aqueous extracts from rye grown at two field locations showed similar inhibitory effects on redroot pigweed and green foxtail. Extracts from rye tissues grown at Winnipeg, MB and Rosebank, MB significantly inhibited germination in redroot pigweed by 33% and 52%, respectively, and green foxtail by 25% and 35%, respectively, compared to water controls (Table 4.15). These effects support results from field studies where incorporating rye's biomass into the soil significantly reduced both broadleaved and grassy weed species compared to controls (Table 4.5, 4.6).

Table 4.14 Germination response of test species subjected to extracts from greenhouse grown fall rye

		% Germination of test species		
Treatment	**Rye Developmental Stage**	**Redroot pigweed**	**Green foxtail**	**Navy beans**
Rye	**4 leaf**	**57 b[z]**	**77 b**	**92 a**
H_20 control		**90 a**	**98 a**	**90 a**

z Means with the same letter are not significantly different

Table 4.15 Germination response of test species subjected to extracts from field grown fall rye

		% Germination of test species		
Treatment (Location)	**Rye Developmental Stage**	**Redroot pigweed**	**Green foxtail**	**Navy beans**
Rye (Winnipeg)	**4 leaf, 3 tiller**	**62 b[z]**	**75 b**	**92 a**
H_20 control		**93 a**	**100 a**	**97 a**
Rye (Rosebank)	**5 leaf , 3 tiller**	**41 b**	**64 b**	**85 a**
H_20 control		**86 a**	**99 a**	**88 a**

z Means with the same letter are not significantly different

Results from this experiment showed that extracts from rye, grown under controlled greenhouse conditions and field environments, significantly inhibited germination of redroot pigweed and green foxtail. Therefore, the rye remained chemically active under various temperature and moisture conditions, fertility regimes, and soil types. It is interesting to note, however, that field tissues from Rosebank, MB were more inhibitory to both weed species than field tissues from Winnipeg, MB. Soil test reports for these two sites, collected prior to rye termination and crop seeding, show that soils at Rosebank had low soil nitrate status during rye's early growth, while soils at Winnipeg, MB had moderate or medium nitrate levels. Soil nitrate levels at the 0-60 cm depth were 52 kg/ha and 110 kg/ha at Rosebank and Winnipeg, respectively. Mwaja et al (1995) observed that rye tissues grown under low fertility regimes were more toxic to cress roots than tissues from rye grown under moderate to high fertility regimes. The enhanced toxicity at low soil nutrient levels was found to be due to an increase in the production of two hydroxamic acids, DIBOA and BOA, in rye. It has also been found that extracts from stressed rye plants are more inhibitory compared to extracts from non stressed plants (Barnes and Putnam, 1986; Rice, 1984).

Results from this study found significant reductions in germination and observable differences in radical length of redroot pigweed treated with extract of fall rye compared to water controls (Table 4.14, 4.15, Fig.4.9). Although radical length was not statically analyzed, visible reductions in radical length were observed in treated seeds compared to controls (Fig.4.9). Green foxtail treated with rye extracts was also found to have significantly reduced germination compared to water controls; however, radicle length was not different (Fig.10). This less pronounced effect on green foxtail compared to redroot pigweed may be attributed, similarly, to results by Barnes and Putnam (1987) who found that DIBOA and BOA were more inhibitory to germination and radicle elongation in dicots compared to monocots.

No significant effects, by greenhouse grown rye extracts, were found on bean seed germination compared to water controls (Table 4.14). To test whether the larger bean seed would be less affected than the small seeded weeds at similar 2 ml volumes of extract, due to less imbibed solution by the larger seeds, additional bioassays on bean

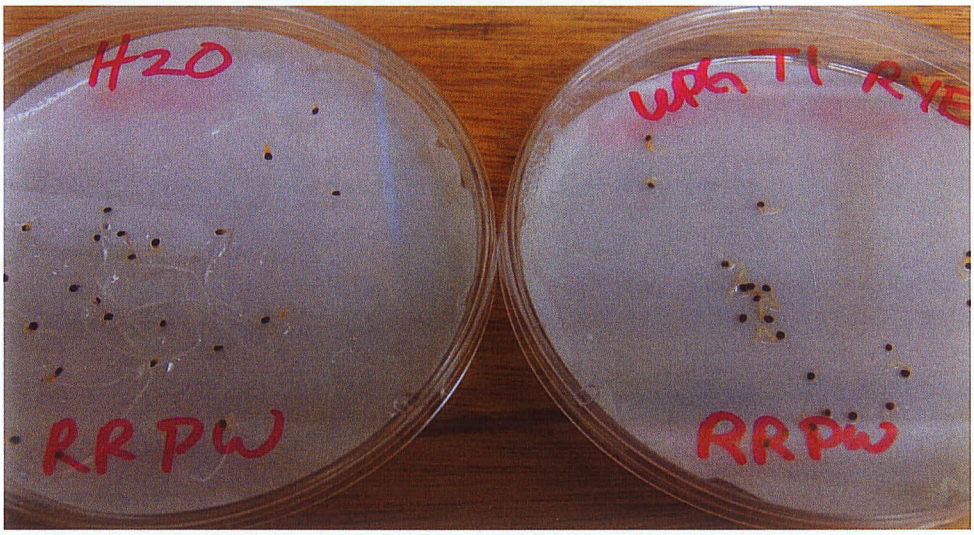

Fig 4.9 Redroot pigweed germination response to water (left) and rye extracts (right)

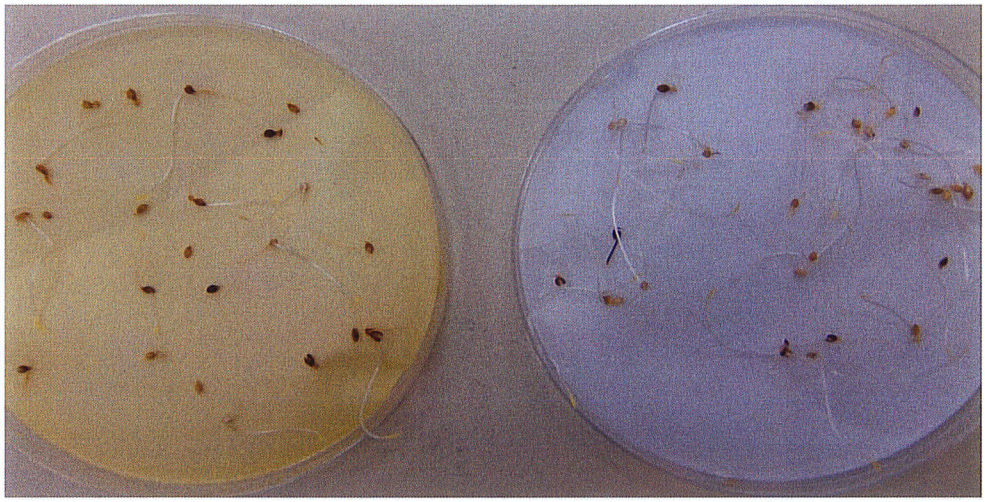

Fig 4.10 Green foxtail germination response to rye extracts (left) and water (right)

seeds using 3ml and 4ml aliquots were performed. At 3ml aliquots, mean bean seed germination was 87% and 90% and at 4ml aliquots, mean bean germination was 85% and 92% for rye extracts and water respectively. Statistical analysis revealed no significant difference in bean seed germination when rye extract volume was increased compared to water controls of similar volumes. This shows that bean seeds, in spite of increased exposure, remain unaffected by rye's phytotoxic extracts. Due to the lack of significance, further bioassay experiments using rye extracts from field grown tissues on bean seeds were performed using 2 ml aliquots, similar to test on weed species.

No significant difference in bean seed germination was found by extracts from rye, grown at either field location, compared to water controls (Table 4.15). In addition, no observable difference on bean radicle length was found by any of the rye extracts tested compared to water (Fig.4.11).

Fig 4.11 Bean seed germination response to water (left) and rye extracts (right)

Results from the previous field study found redroot pigweed and green foxtail exhibited significantly lower population densities following fall rye cover crops (Table 4.5). Bioassay results with these same two weeds showed significantly reduced germination responses when treated with aqueous extracts from rye compared to water. Studies by Putnam and DeFrank (1983) and Shilling et al. (1985) showed that rye residue extracts containing the hydroxamic acids DIBOA and its breakdown product BOA are responsible for inhibiting germination of redroot pigweed and green foxtail, however, the mode of action of these chemicals was not clearly defined by these authors.

These combined results of field and bioassay experiments suggest allelopathic influences from fall rye do occur and that suppression witnessed under field conditions should be, in part, attributed to this phenomenon. Although dry bean establishment, development and yield was found in one of four field experiment site-years to be significantly reduced following a rye cover crop (Table 4.8, 4.10, 4.11), bioassays on

bean seeds found that rye extracts did not significantly reduce germination compared to water controls. This gives additional support to the previously proposed theory that observed negative effects on dry beans following rye under field conditions, was most likely the result of drought conditions in 2006 combined with significant water usage by the cover crop prior to bean production, not allelopathic influences by the cover crop.

In regards to the differential effects of rye extracts on weed and bean seed germination, it may be useful to refer to the work of Romero-Romero et al (2002) and Cruz-Ortega et al (2002) who suggested that beans have defense mechanisms induced in response to allelochemical stress. Although the specific chemistry and exact mode of action of the allelochemicals produced by the species in the studies by Romero-Romero et al (2002) and Cruz-Ortega et al (2002) were not known, it may be possible that the common bean has naturally developed defense strategies to cope with allelopathic stress. The results and discussions by the authors in these studies indicate that beans have the ability to defend against allelopathic stress from several different plant sources. This evidence, combined with results from this study give support to suggest that beans, unlike the weed species in this study, may have mechanisms to defend against allelchemical stress from fall rye.

4.6 Bioassays with crude aqueous extracts from three winter cereals

While determining the effects of rye extracts on weed and bean seed germination, a new question regarding the possibility that allelopathy exists in other cereal cover crops arose and became: Do winter wheat and winter triticale possess similar allelopathic attributes? To answer this question, bioassays involving the same two weeds, redroot pigweed and green foxtail and dry beans were subjected to extracts of field grown winter wheat and winter triticale, in addition to fall rye. The results from this study showed that allelopathy does exist in all three cultivars tested; however, their effects are quite diverse.

Aqueous extracts of all cover crops significantly reduced germination in redroot pigweed compared to water controls (Table 4.16). Germination response of redroot pigweed to cereal cover crop extracts and controls were 48%, 50% and 49% and 86% for fall rye, winter triticale, winter wheat and water controls respectively. No significant differences in redroot pigweed germination were found when cover crop extracts

treatments were compared (Table 4.16). Aqueous extracts of all cover crop extracts significantly reduced germination in green foxtail compared to water controls (Table 4.16). Germination response of green foxtail to cereal cover crop extracts and controls were 75%, 64% and 76% and 100% for fall rye, winter triticale, winter wheat and water controls respectively (Table 4.16). Unlike redroot pigweed, green foxtail germination response was significantly different among cover crop extract treatments (Table 4.16). Comparison between rye and winter wheat extracts on green foxtail germination found no significant differences (Table 4.16). Winter triticale extracts, however, were most inhibitory and found to significantly reduce green foxtail germination compared to winter wheat and fall rye by an additional 14% and 13%, respectively (Table 4.16).

Table 4.16 Germination response of test species subjected to extracts from three winter cereal cover crops

	% Germination of test species			
			Exp. 1	Exp.2
Cereal cover crop	**Redroot pigweed**	**Green foxtail**	**Navy beans *cv.* Envoy**	
Fall rye *cv.* Remington	**48 b[z]**	**75 b**	**88 a**	**93 a**
Winter triticale *cv.* Pika	**50 b**	**64 c**	**67 b**	**53 b**
Winter wheat *cv.* Buteo	**49 b**	**76 b**	**30 c**	**35 c**
H20 control	**86 a**	**100 a**	**88 a**	**93 a**

z Means with the same letter are not significantly different

Results from this experiment found that extracts from all three winter cereal cover crops affected redroot pigweed germination equally, which may suggest the allelochemicals produced by the three cover crops exert a similar force and/or follow a similar mode of action in redroot pigweed. Fall rye extracts and winter wheat extracts were not found to be significantly different in their action on green foxtail germination. This may indicate their individual toxic affects are similar in this weed species or perhaps their individual allelochemicals use different, yet equally effective, modes of action in this species. Winter triticale extracts were found to be most suppressive to green foxtail.

It could be theorized that winter triticale, being the cross of rye and wheat, may be exhibiting some form of hybrid vigor, producing all parental allelochemicals, possibly working synergistically by a single mode of action or by affecting several processes in the seed simultaneously. This could include DIBOA acting on membrane enzymes and MBOA on α-amylase enzymes. Being that allelochemicals are known to be selective and species specific may indicate why green foxtail, unlike redroot pigweed, was sensitive to this effect by winter triticale.

Dry bean germination response to treatments were 88%, 67%, 30% and 88% for extracts from fall rye, winter triticale, winter wheat and water respectively (Table 4.16) Aqueous extracts of field grown fall rye produced the same germination response from dry bean as water controls and no significant difference between these two treatments was observed (Table 4.16). Conversely, aqueous extracts of field grown winter triticale and winter wheat were found to significantly differ in their effects on germination in beans compared to rye and water controls (Table 4.16). Winter triticale extracts were moderately inhibitory and caused a 24% reduction in germination of dry beans compared to fall rye extracts and water controls (Table 4.16, Fig 4.12). Winter wheat extracts were the most inhibitory, as their effects led to a 66% reduction in germination in dry bean compared to fall rye extracts and water controls (Table 4.16, Fig 4.13). A repeat of this experiment produced the same statistical results (Table 4.16). This observation shows that winter wheat is highly allelopathic to dry beans. Therefore, dry bean producers should be warned against its use as a cover crop.

No significant differences in germination of redroot pigweed and green foxtail were detected between the aqueous extracts from fall rye compared to winter wheat, however, winter wheat significantly reduced dry bean germination by 66% compared to fall rye. A possible explanation for this observation may be related to work by Romero-Romero et al (2002) and Cruz-Ortega et al (2002) who suggested that common bean may have defense mechanisms that are induced in response to certain alleopathic stresses. Therefore, it may be possible to suggest that allelochemicals from winter wheat are having a differential effect on defense system activation in dry beans compared to extracts from fall rye, thus allowing the inhibitory effects of winter wheat extracts to become apparent.

The results from the present study combined with evidence from previous studies make it possible to suggest that DIMBOA, being highly reactive (Friebe et al, 1997, interferes with enzymes in dry bean seeds required for the activation of defense proteins, such as α-amylase inhibitors as described by Cruz-Ortega et al (2002). DIMBOA also deactivates proteases—an enzyme that conducts proteolysis, that is, it breaks apart proteins— (Perez and Niemeyer, 1989) Working to determining the mechanisms required for the activation of α-amylase inhibitor defense proteins in common bean, Pueyo et al (1993) found that in order for an α-amylase inhibitor to be activated, it needed first be processed by a protease which broke apart the molecule and removed a conformational constraint. If this proteolytic process did not occur and the molecular constraint was not removed, this bean α-amylase inhibitor would remain inactive. Therefore, if defense systems were not being activated, it would seem reasonable to expect an allopathic effect on beans such as α-amylase inhibition or plasma membrane degradation (Kato-Noguchi and Macias, 2006; Friebe et al, 1997), thus explaining the low germination response in dry bean seeds treated with winter wheat extracts compared to extracts from fall rye. Triticale, the resultant cross of rye and wheat, was found to be intermediate in its inhibitory effects on bean seed germination in this experiment. This may suggest triticale inherited the ability to produce all allelochemicals from both parents; however, it would appear triticale's suppressive chemical attributes are not absolute.

Finally, it may be of interest to mention a few field studies assessing dry bean and soybean performance following various cover crops. Webber and Shrefler (2004) found that black beans following rye cover crops produced the highest yields, whereas black beans following winter wheat produced the lowest yields of four cover crops tested. Valentini et al (2001) found that among cover crops used in their study, which included ryegrass, white oat, black oat and wheat, final bean populations and yield were lowest following the wheat cover crop and Price et al (2006) found soybean yields were highest following rye, followed by black oat and lowest following wheat.

In conclusion, all three cover crop extracts were found to significantly reduce germination in two weed species tested compared to water controls, extracts from fall rye alone produced the same result from beans as water controls. The reasons for this lack of

effect by rye on bean seed germination are not entirely clear, however, the conclusion that beans are unaffected is most important for producers.

This work not only indicates that allelopathy exists in the cultivars tested, but it also provides additional evidence to support fall rye cover crop use in dry bean production.

Fig 4.12 Dry bean germination response to extracts of fall rye (left) and winter triticale (right)

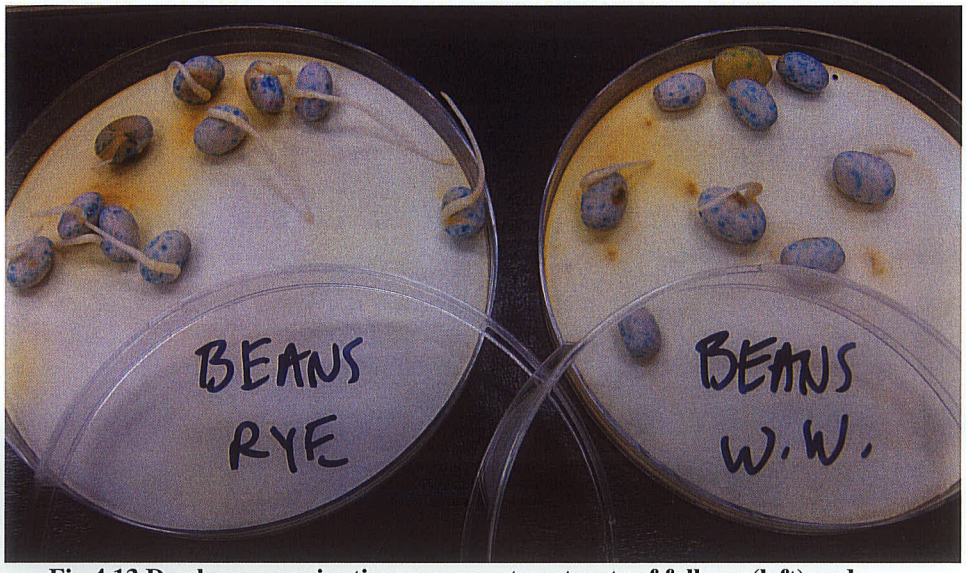

Fig 4.13 Dry bean germination response to extracts of fall rye (left) and winter wheat (right)

5.0 GENERAL DISCUSSION

The main objective of this study was to determine the impacts of a rye cover crop on two plant species populations, weeds and dry beans. Rye's competitive ability, high early season biomass production, and allelochemical production allow this cover crop to limit neighboring plant populations by suppressing them both physically and chemically. Therefore, it was of interest to determine if a rye cover crop prior to dry bean production could effectively reduce weed populations such that future cropping systems utilizing rye cover crops might be less reliant on herbicides. Additionally, it was hoped that rye's potential suppressive effect on weeds would not affect the dry bean crop. Instead, other beneficial attributes of rye, such as improved seedbed conditions through the removal of excess spring moisture, increased soil aeration, improved water infiltration, late season soil moisture conservation and nutrient cycling would enhance bean crop productivity. To this end, this research has helped define certain boundaries regarding rye cover crop use, including rye's differential effects on a range of plant species, cautions regarding water usage by the cover crop, the ideal growth stage for terminating the cover crop and managing the residues. This was the first such study in Manitoba history.

In regards to rye's weed suppressing abilities, results from this study indicate that this cover crop has a powerful effect on reducing initial weed population densities and accumulated weed biomass. This study found that rye, in the absence of herbicides, consistently reduced early broadleaved weed densities and total broadleaved weed biomass at all site-years under study. Rye also significantly reduced initial grass weed populations; however, rye's effects on grass weed densities and biomass were less consistent and less pronounced compared to rye's effects on broadleaved weeds. These results suggest there is potential for dry bean producers to limit herbicides, particularly for broadleaf weed control, provided rye cover crops are present before bean production.

Although previous research has shown that greater weed suppression, by rye, is achieved when cover crop biomass is increased (Teasdale et al, 1991), this research found that rye terminated and incorporated at the four leaf stage provides the same level of weed suppression as when the cover crop was terminated at booting or heading, when more than twice the amount of biomass was incorporated into the soil. This was a very

important observation because it suggests that very little cover crop biomass is required to achieve substantial weed suppression. By terminating the cover crop early, there would be less risk of soil moisture depletion and nutrient use, by rye. Therefore, producers following this early termination guideline for rye cover crop use would be able to capture the full weed suppressing effects of the cover crop while limiting potential negative effects to their bean crops.

Interestingly, observations of some of these sites showed such small quantities of rye residues were present in the soil when terminated at its early stage, that any physical effects by the residues would be considered negligible. However, season long effects on weeds by rye were found, suggesting that other factors attributed to the cover crop were interfering with weed success. Allelopathy was proposed to be such a factor attributed to rye's suppressive effects. Investigations with extracts from fall rye tissues showed that weed seeds treated with these extracts exhibited markedly lower germination compared to seeds treated with water, indicating that rye does in fact produce phytotoxic compounds, or otherwise, is allelopathic. Previous research found that rye residues can preserve these preformed phytotoxic compounds for over five months (Yenish et al, 1995), therefore, season long weed control, by rye, observed in this study may be attributed to the slow release of allelopathic substances as the residues decomposed.

Good weed control, particularly broadleaf weed control, is necessary, as dry beans are poor competitors with weeds. Therefore, dry bean producers are often advised to apply a pre-emergent herbicide to limit early season weed competition and a post-emergent herbicide to limit late season weed pressure (SPG, 2000, MAFRI, 2006). With respect to this current advisement, the results from this study showed that incorporating a rye cover crop at an early developmental stage provides significant early and late season weed control over a range of weeds, with broadleaved weeds being largely and more consistently affected than grass weeds. These results may suggest that when a rye cover crop is present before dry bean production, additional herbicides need to be supplemented only if necessary. Hence, dry bean production systems looking to reduce herbicide inputs would benefit from including a rye cover crop in rotation. In the event that herbicides are applied, results from this study suggest rye residues can minimize injury to the bean crop by intercepting excess herbicides. Furthermore, with thought to herbicide resistant weeds,

rye may have novel chemistry and modes of action compared to current herbicides, which may help alleviate weed resistance problems.

Producers looking into implementing a rye cover crop often asked if the rye will hurt the bean crop. This study found that rye did not negatively affect bean establishment, development, height, biomass or yield in three of four site-years. To address the issue of allelopathy, bioassays on bean seeds using fall rye extracts showed, in repeat experiments and under increasing volumes of extracts, that bean seed germination was not affected. This evidence combined with field observations in which beans following rye produced similar yields in two of four site-years and an increase in yield in one of four site- years, compared to controls, is reason enough to suggest that dry beans are tolerant to rye's phytotoxic nature. Therefore, bean producers with reservations regarding rye cover crop use can be assured that allelopathic effects, by rye, are not a concern.

Once allelopathy was eliminated as a source for the negative response of beans observed in one site-year, other factors in the field such as water usage by the cover crop, physical effects from the residues, environmental conditions during the growing season and soil type and texture of the seedbed were addressed and subsequently ruled out or concluded to be the problem. At Carman, MB, in 2006, dry beans responded poorly for all growth and development parameters measured following the cover crop. The most reasonable explanation for these results was the observed high water usage by the cover crop compared to controls prior to bean establishment. In review, the summer of 2006 was quite hot and dry, leading to heat and moisture duress at both the Carman and Rosebank sites. However, beans did not exhibit the same negative response following the cover crop at Rosebank as they did at Carman. Carman has a different soil type than other site-years, with lighter, sandier soils compared to the heavier clay soils found at other sites. In addition, fall rye was seeded, in 2005, at a higher rate at Carman compared to Rosebank in 2006. This resulted in close to 1000 kg/ha of additional rye biomass being present at Carman at the early termination compared to Rosebank. Therefore, to prevent excess water usage by the cover crop on lighter textured soils, it may be beneficial to seed fall rye at a slightly lower seeding rate in the fall and then terminate it as soon as wind erosion risks have subsided and conditions are such that there is easy access to the field. In a wet year, it may be beneficial to allow the cover crop to grow longer, however,

results from this experiment suggest rye can be terminated as early as the fourth to fifth leaf and still provide weed suppression benefits. Heavier soils may benefit from a higher rye seeding rate, particularity if excess moisture and/or salinity are an issue.

Turning the focus to the positive effects of the cover crop on dry beans, the results from this study indicate that rye may have benefits for dry bean beyond weed suppression. For example, at Winnipeg, yields were found to increase following rye compared to control treatments, although visual field observations would have indicated otherwise. For much of the growing season at both Winnipeg and Rosebank, dry beans following rye displayed slightly less vigor and at times symptoms of stress; however, as late maturity approached, there appeared to be a recovery in the crop. It may be possible that there was a nutrient stress on beans following the cover crop since rye has high N requirements and dry beans have relatively low N-fixing abilities compared to other annual pulse crops (SPG, 2000). Therefore, it is possible that rye did remove excess nitrogen that may or may have not been released back through mineralization from residues. However, it would appear that rye provided some other benefit that enhanced bean productivity.

The spring of 2007 began with above average precipitation; however, as summer temperatures increased and precipitation fell, moisture became limited. Therefore, rye's presence in the spring may have helped to aerate the soils at Winnipeg and redistribute water throughout the soil profile, possibly by channels formed by rye's proliferating roots. Then as the season progressed, rye residue, at or near the soil surface may have helped to keep the soil cooler and moister. Residues from terminated cover crops are known to increase water infiltration and reduce evaporation, resulting in less moisture stress to the following crop (Bowman et al, 1998). Moisture stress during flowering and early pod-fill can reduce dry bean yield (SPG, 2000), therefore, this increase in yield observed at Winnipeg was likely due to rye residues conserving moisture during this crucial period.

It was observed that beans grown on soils tilled seven to ten days before bean seeding, grew better than beans seeded immediately following tillage (i.e., where pre-seeding tillage was delayed until immediately before bean seeding). Although soil temperatures were not measured in this study, it was thought that earlier tillage led to

improved soil drying and thus warming, which contributed to improved bean growth, development and yield (Balasubramanian et al 2003). Therefore, producers might be advised, particularly in heavier clay soils, to begin seedbed preparation at least a week in advance of seeding to improve productivity of the crop.

As previously mentioned, dry bean producers aware of this study indicated concern over rye being allelopathic to their crop and therefore, inquiries had been made regarding using a winter wheat cover crop in substitution of rye to avoid such a problem. Although field trials were not possible in this study, bioassays using field grown tissues of winter wheat, winter triticale and fall rye showed that winter wheat was extremely allelopathic to bean seeds. Winter triticale was moderately allelopathic and fall rye produced the same effects on bean seeds treated with water. These results indicate that winter wheat and winter triticale may not be suitable cover crops to use in dry bean production. Further research with field trials may help to shed more light on dry bean response to these other cover crops. However, as indicated by this research, fall rye appears to show the greatest potential for dry bean production.

In conclusion, these findings suggest that a well managed fall rye cover crop can provide benefit to beans by effectively controlling weeds prior to seeding, thus giving the crop a competitive start. This in turn may allow for elimination of pre-emergent herbicides as well as an overall reduction in the need for post emergent herbicides. In addition, rye's presence in the spring may provide better water infiltration prior to cover crop termination and residues will help conserve moisture throughout the growing season, thus furthering the success of the bean crop. Allelopathic effects by the cover crop on the bean crop are not a concern. Lastly, the rye cover crop also provides erosion control during the late fall, late winter and early spring period.

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