Quantification of Persian darnel (Lolium persicum) interference in monoculture, spring wheat, canola and sunflower
by Johnathon Douglas Holman

A thesis submitted in partial fulfillment of the requirements for the degree Master of Science in Land Resources and Environmental Sciences
Montana State University
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Abstract:
Persian darnel (Lolium persicum) is a potentially serious weed of cereal production in the northern Great Plains. However, the impact of Persian darnel on crop yield has not been quantified. Producers are managing this weed with a range of weed control practices. In some instances management practices have lost their effectiveness.

Integrated weed management practices, such as crop rotation, might improve the management of Persian darnel. This thesis quantifies the effect of crop type and crop seeding rate on Persian darnel fecundity and impact on crop yield. Experiments were established in Bozeman, MT in 2000 and 2001. Crops were seeded at 1X, 1.5X and 2X the MSU recommended rate, and Persian darnel was established to create a range of densities from 0 to 2,000 seedlings/m2. Yield was related to crop and weed seedling densities, using a combined modified hyperbolic function. Increasing crop density increased crop yield and often reduced weed fecundity. Crop seeding rate was inefficient at increasing crop yield or reducing weed fecundity, likely due to variability in crop seedling establishment. Crop yield loss was estimated to reach 83%, 70% and 57% for spring wheat, canola and sunflower, respectively at high Persian darnel densities. Persian darnel had the least impact on sunflower yield likely due to lower weed densities following a pre-plant application of glyphosate and rooting to shallower depths than sunflower. Persian darnel was found to reduce crop yield components at early stages of crop physiological development, indicating interspecific interference occurred early in the growing season. Persian darnel reduced crop quality and price of spring wheat and canola by increasing weed dockage, but did not increase dockage in sunflower. Persian darnel produced up to 800 seed per plant at low crop and weed densities. Increasing canola and, spring wheat density reduced Persian darnel fecundity independent of herbicides. The largest potential impact of crop on Persian darnel fecundity was by decreasing weed seedling establishment. Persian darnel seedling establishment was reduced 99% and 70% in sunflower, while canola reduced Persian darnel seedling establishment 90% and 25% compared to monoculture in 2000 and 2001, respectively. Cultural management will enhance the management of Persian darnel and improve the efficacy of other practices such as selective herbicides.
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INTERFERENCE IN MONOCULTURE, SPRING WHEAT, CANOLA AND
SUNFLOWER

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 4/21/02
Dedicated to my father

Douglas Arvin Holman
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Abstract.

Persian darnel (Lolium persicum) is a potentially serious weed of cereal production in the northern Great Plains. However, the impact of Persian darnel on crop yield has not been quantified. Producers are managing this weed with a range of weed control practices. In some instances management practices have lost their effectiveness. Integrated weed management practices, such as crop rotation, might improve the management of Persian darnel. This thesis quantifies the effect of crop type and crop seeding rate on Persian darnel fecundity and impact on crop yield. Experiments were established in Bozeman, MT in 2000 and 2001. Crops were seeded at 1X, 1.5X and 2X the MSU recommended rate, and Persian darnel was established to create a range of densities from 0 to 2,000 seedlings/m². Yield was related to crop and weed seedling densities, using a combined modified hyperbolic function. Increasing crop density increased crop yield and often reduced weed fecundity. Crop seeding rate was inefficient at increasing crop yield or reducing weed fecundity, likely due to variability in crop seedling establishment. Crop yield loss was estimated to reach 83%, 70% and 57% for spring wheat, canola and sunflower, respectively at high Persian darnel densities. Persian darnel had the least impact on sunflower yield likely due to lower weed densities following a pre-plant application of glyphosate and rooting to shallower depths than sunflower. Persian darnel was found to reduce crop yield components at early stages of crop physiological development, indicating interspecific interference occurred early in the growing season. Persian darnel reduced crop quality and price of spring wheat and canola by increasing weed dockage, but did not increase dockage in sunflower. Persian darnel produced up to 800 seed per plant at low crop and weed densities. Increasing canola and spring wheat density reduced Persian darnel fecundity independent of herbicides. The largest potential impact of crop on Persian darnel fecundity was by decreasing weed seedling establishment. Persian darnel seedling establishment was reduced 99% and 70% in sunflower, while canola reduced Persian darnel seedling establishment 90% and 25% compared to monoculture in 2000 and 2001, respectively. Cultural management will enhance the management of Persian darnel and improve the efficacy of other practices such as selective herbicides.
REVIEW OF LITERATURE

*Lolium persicum*

Origin and Distribution

Persian darnel (*Lolium persicum* Boiss. & Hoh.) is an introduced, cool-season, C₃ grass that has invaded and established in the northern Great Plains. The impact of Persian darnel on crop yield has not been reported, but speculations suggest that it can reduce crop yield and contaminate harvested grain (Banting and Gebhardt 1979; Hunter 1995; Rardon and Fay 1981). Few management options are currently available for managing Persian darnel. Persian darnel originated in northern Iran to central Asia (Dore 1950). Persian darnel was first reported in North America in Cavalier County, North Dakota in 1911 and Saskatoon, Canada in 1923 (Dore 1950; Forcella and Harvey 1988). Persian darnel was first reported in Montana in 1954, and currently infests 26 counties (Montana State University herbarium 1998; Wilderness Invaders Project 2002). Persian darnel is primarily found in cultivated fields, and can be found along riverbanks, and stony slopes (Frankton and Mulligan 1970).

Morphology

Persian darnel is an annual grass that reproduces by seed, tillers at the base, stands erect and reaches 15 to 45 cm in height. Leaf blades are long and narrow (2 to 6
Leaves are light green in color and have a luminous appearance. Leaves are rough on the upper surface and margins and smooth on the underside. Second and later emerging leaf blades have prominent veins above and a midrib below the leaf surface. The ligules are membranous and short with a smooth margin. Auricles are generally present only on later developing leaves and are short (2 mm long) (Charmet and Balfourier 1994; Frankton and Mulligan 1970).

Spikelets are in two rows arranged dorsally of the rachis. Each spikelet contains five to seven florets. The seed is enclosed in a lemma and palea that remain on the seed when threshed. The narrow lemma has a slender awn attached at the tip, and the awn is equal to the lemma in length. The seeds are 6 mm long, 1.5 mm wide, and are mostly light-colored (Frankton and Mulligan 1970; Charmet and Balfourier 1994; Hunter 1995). Persian Darnel is a diploid species (2n=14), and is self-pollinated (Charmet and Balfourier 1994; Terrell 1968).

Seed Biology

Persian darnel seed was found to germinate in the lab at temperatures greater than 10 C with maximum germination occurring at 20 C (Banting and Gebhardt 1979; Bussan et al. unpublished data). Bussan et al. (unpublished data) found Persian darnel failed to germinate when temperatures reached 30 C (Figure 1). Light was also found to increase germination as an 8 h light/16 h dark period increased seed germination 25% over complete darkness (Banting and Gebhardt 1979). Reportedly, Persian darnel typically germinates during early spring but then tapers off (Hunter 1995). Few if any Persian darnel plants have been found to emerge in production fields after soil
temperatures warm to 25-30°C. The anecdotal data on Persian darnel germination and
time of emergence corresponds to the results found in the lab.

Banting and Gebhardt (1979) found seeds kept dry and at a constant temperature
of 20°C rapidly lost their dormancy. In contrast, dormancy persisted longer at
temperatures less than 1°C. Persian darnel dormancy was lost more rapidly when
germination temperatures fluctuated compared to constant temperatures. The effect of
alternating temperature on dormancy has been observed in other grass species as well
(Bello et al. 1998; Hardegree et al. 1999; Hardegree and Van-Vactor 1999). Dormancy
of Persian darnel seed was lost quicker when temperature fluctuated from -3 to +20°C,
than from +1 to +20°C (Banting and Gebhardt 1979). Persian darnel seed stored under
moist soil conditions lost their dormancy quicker under alternating temperatures of -3 to
+20°C than those stored under a constant temperature of 20°C or an alternating
temperatures of +1 to +20°C (Banting and Gebhardt 1979). In the northern Great
Plains, extreme temperature fluctuations can occur through the winter and early spring.
The temperature fluctuations found in the northern Great Plains might increase Persian
darnel seed afterripening and germination.
Banting and Gebhardt (1979) found minimal differences in Persian darnel emergence at depths of 5 cm or less across soil types ranging from sandy loam to heavy clay. Emergence was the greatest in heavy clay soil at a depth of 7.5 cm, and little to no emergence occurred at depths greater than 7.5 cm. Chepil (1946) similarly found Persian darnel emergence to be the greatest in clay, followed by loam and then sandy loam soils at a depth of 7.6 cm. Within 12 to 18 months 100% of the seed had germinated and were no longer viable if buried. In contrast, 90% of the seed left on the soil surface had died within 2 years and less than 2% of the seed remained viable after 3 years (Banting and Gebhardt 1979). Part of the reason that seed left on the soil surface persisted longer than buried seed was because seed predation was excluded. However, field observations suggest Persian darnel has become more problematic in recent years. This might be due to increased use of reduced tillage or direct seeding systems, leaving the seed on the soil surface enabling Persian darnel to germinate in subsequent years.
Growth and Development

Persian darnel time of emergence is similar to spring wheat (*Triticum aestivum* L.) and wild oat (*Avena fatua* L.), beginning in mid April to early May and ending in early June for the majority of MT and southern Saskatchewan (Banting and Gebhardt 1979; Hunter 1995). Early season emergence and rapid development of Persian darnel might provide a competitive advantage, especially in spring seeded crops and resource-limited environments (Banting and Gebhardt 1979; Evetts and Burnside 1972). Early resource capture, especially soil moisture, is critical in dryland cereal production where stored soil moisture and early season rainfall are essential for crop growth and yield (Evetts and Burnside 1972; Kropff et al. 1992; Patterson 1995). Weeds that emerge after the crop are less competitive and produce fewer seeds than early emerging weeds (Knezevic et al. 1997; Mickelson and Harvey 1999; Smith and Jordan 1993).

In addition to direct effects of competition on yield, Persian darnel might cause significant economic losses as contaminant of harvested grain. Early and late maturing Persian darnel tillers might retain seed and be harvested with the crop resulting in contamination. In a non-peer reviewed report, Persian darnel was suspected of spreading by seed contamination (Rardon and Fay 1981). A delay in harvest might reduce seed dispersal in the field and dockage, but will not eliminate contamination (Shirtliffe et al. 2000).

Information on the nutrient requirements of Persian darnel is limited. Preliminarily, Hunter (1984) found that applying fertilizer at a high rate in spring wheat, reduced Persian darnel biomass 20%, and increased spring wheat yield 54%.
Unfortunately, no explanation was given as to why a high rate of fertilizer increased crop yield and decreased Persian darnel biomass. The increased competitive ability of spring wheat might have been attributed to an increased proportion of fertilizer taken up by spring wheat. The increased level of fertilizer available to spring wheat might have also increased crop competitiveness with Persian darnel by increasing spring wheat rate and amount of vegetative growth, limiting light availability for Persian darnel.

Nutrient research has been conducted on two species related to Persian darnel: annual ryegrass (Lolium multiforum Lam.) and perennial ryegrass (Lolium perenne L.). Studies have shown that Lolium spp. have high phosphate utilization efficiency and that increases in available phosphorus, calcium and magnesium are correlated with increased growth (He et al. 1999; Hillard et al. 1992). Annual ryegrass intercropped with corn (Zea mays L.) resulted in decreased levels of nitrogen available for corn (Zhou et al. 1997). It is possible; fertilizer placement and composition might influence Persian darnel interference with crop growth.

Data has not been published on the rooting characteristics of Persian darnel. However, it is likely that Persian darnel has a fairly shallow rooting depth due to its short growing period. Furthermore, Murphy and Smucker (1995) found that a related species, perennial ryegrass has a very fine, fibrous, shallow rooting system, with a total root length of 10 m. Dardanelli et al. (1997) measured the rooting depth and extension rate for five crops. The results concluded that root extension ceases at the time of grain fill. Persian darnel initiates grain fill several weeks ahead of spring wheat, and therefore might cease root growth earlier than spring wheat.
Emigration

In 1976, fifty-six years after Persian darnel was first reported in North America, Persian darnel was reported in 17 of 41 Agricultural Extension Districts in Saskatchewan (Dore 1950; Hunter 1995). Over the course of fifty years, Persian darnel had developed infestation levels high enough to encourage expensive management and crop yield loss over a wide geographic area. Currently, the same trend of wide geographic and economic impact is occurring in Montana (Wilderness Invaders Project 2002) (Figure 2). In 1954, Persian darnel was first reported in Montana in Daniels County, and four years later in Fergus County (Wilderness Invaders Project 2002). It is uncertain how Persian darnel was introduced into Montana, but it is suspected that it entered from Saskatchewan, Canada as a contaminant of clover seed (Fay 1995). Today, Persian darnel infests approximately 250,000 ha in 26 Montana counties (Wilderness Invaders Project 2002). It has been suggested that some growers may not identify Persian darnel because it does not grow above the crop canopy, or that it is misidentified as either wild oat or spring wheat (Rardon and Fay 1981). Failure to identify Persian darnel could lead to mismanagement and high seedbank densities before management begins.

Producers have indicated an increasing need to manage for Persian darnel at many locations across Montana (Bussan, personal communication). It has been suggested that darnel might becoming an increasing problem due to reduced tillage systems and increased use of chemical fallow (Banting and Gebhardt 1979).
Management Strategies

Cultural and chemical practices are viewed as essential components of integrated Persian darnel management systems. Cultural management strategies for controlling Persian darnel include planting clean seed, crop rotation, tillage, increased crop competition and delayed crop seeding (Banting and Gebhardt 1979; Hunter 1995). In conventional systems, tillage promotes early season Persian darnel germination and emergence by incorporating weed seed with the soil and warming the soil temperature to induce germination. Once weed seedlings have emerged, Persian darnel seedlings can be managed with a second tillage or burndown herbicide treatment (stale seedbed technique) (Hunter 1995; Buhler and Gunsolus 1996; Spandl et al. 1999). In no-till systems, similar strategies can be employed by allowing soil temperatures to warm and soil moisture to accumulate, inducing Persian darnel seedling emergence. A delay in crop seeding can allow weed seedling emergence to occur prior to seeding. However, a
delay in seeding spring wheat or canola (*Brassica napus* Koch.) can result in reduced
crop yield (Banting and Gebhardt 1979; Buhler and Gunsolus 1996). In the northern
Great Plains, crop rotations that include warm-season crops have the most potential to
successfully utilize the stale seedbed management technique (Buhler and Gunsolus
1996; Spandl et al. 1999).

Selective chemical management options for Persian darnel in crop are limited,
especially in cereal crops. Persian darnel has been controlled in the past with diallate
(no longer labeled) and triallate (Hunter 1995; Bussan et al. 2002). Since the mid
1980’s, herbicides that inhibit the acetyl CoA carboxylase (ACC-ase) pathway have
been labeled for control of Persian darnel in cereal crops; including diclofop,
tralkoxydim and clodinofop (Bussan et al. 2002). ACC-ase inhibition is the only mode
of action labeled for selective post-emergence control of Persian darnel in cereal crops.
Unfortunately, Persian darnel biotypes resistant to ACC-ase inhibitors have been
identified in Montana cereal fields (Weed Science Organization 2002).

Diclofop applied after the three-leaf stage of Persian darnel or during
unfavorable growing conditions resulted in inconsistent control (Hunter 1995).
Preliminarily, Bussan and Dietz-Holmes (2000) found that herbicides applied at the 2-4
If stage of spring wheat reduced Persian darnel fecundity more than when applied at
either earlier or later growth stages. However, herbicides applied earlier, at the 1-2 If
stage of spring wheat, resulted in the highest crop yield.

Other primary Montana crops where Persian darnel might cause yield loss
include sunflower (*Helianthus annuus* L.) and canola. Herbicide modes of action with
efficacy on Persian darnel and labeled for use in sunflower include, ACC-ase
(sethoxydim), root inhibitor (ethafluralin or trifluralin), and lipid synthesis inhibitor (EPTC) (Bussan et al. 2002). Persian darnel can be controlled in canola with ACC-ase (sethoxydim or quizalofop), root inhibitor (trifluralin), EPSP synthase inhibitor (glyphosate tolerant varieties), or acetolactate synthase (ALS) inhibitor (imidazolinone tolerant varieties) herbicides (Bussan et al. 2002). Rotation to these or other crops, allows for rotation of herbicide mode of action.

Crop rotation could improve Persian darnel management and reduce the potential for development of herbicide resistance if herbicides with different modes of action are used. The short seedbank longevity of Persian darnel (Banting and Gebhardt 1979) and rotation to herbicides of different modes of action should effectively manage ACC-ase resistant biotypes.

Herbicide costs have increased both monetarily and socioeconomically (Colbach and Debaeke 1998; USDA 2000). The USDA price index for the entire agricultural producing sector indicates that herbicide and other agricultural producing input costs have been increasing, while prices received have decreased (Figure 3). The negative correlation of agriculture input costs to prices received indicates that the production sector is paying more to raise a crop, while receiving less for the commodity. The socioeconomic cost of herbicides has increased with consumer awareness and concern for potential harmful pesticide effects on the environment. Studies have shown cultural weed management systems can be more profitable than herbicide based systems while maintaining low weed densities (Wiese et al. 1997). Furthermore, organic farming has started to show some potential of being an economically sustainable system (Derksen et al. 2002). Organic farming is economically supported by consumer willingness to pay
more for food because they believe food grown in a conventional system might have the potential of containing pesticide residues on the food (Lee 1992).

Figure 3. USDA reported price index of the entire agricultural production sector for 2000. Prices paid for input costs of production, and prices received for production commodity at the production level.

Interference With Crop Growth

Reportedly, Persian darnel interference has caused crop yield loss (Hunter 1984, 1995). In a non-peer review report, Persian darnel was found to be as competitive with spring wheat (*Triticum aestivum* L.) as wild oat (*Avena fatua* L.) in dryland production systems (Fay 1995; Hunter 1984). Persian darnel densities have been quantified to exceed 2800 plants/m² in dryland wheat production (Hunter 1984). Preliminarily, Persian darnel densities of 30 plants/m² resulted in a 15% yield reduction of spring wheat (Hunter 1984). It has been suggested that the early emergence and growth of Persian darnel might enable it to be competitive with spring crops (Banting and Gebhardt 1979). In areas where Persian darnel is found, including Montana, crop
growth is primarily dependant on stored soil moisture. These areas commonly receive little growing season precipitation and frequently incur drought stress late in the growing season causing early senescence. It is theorized that early season water use by Persian darnel might enable it to cause extensive crop yield loss under moisture-limiting conditions, while still enabling it to produce seed (Banting and Gebhardt 1979; Hunter 1995).

Justification for Research

Influence of Crop Rotation on Weed Populations

Crop rotation is seen as a key management tool in integrated weed management systems (Buhler et al. 1997; Derksen et al. 2002; Doucet et al. 1999). Weed management efficacy is increased with increasing crop diversity and rotation (Entz et al. 1995; Le’ge’re and Samson 1999; Liebman et al. 1996). The weed community reflects resource availability, either abiotic or biotic, in a cropping system (Buhler et al. 1997; Le’ge’re and Samson 1999). Abiotic resources include light, water, nutrients and other environmental resources; biotic resources include nitrogen fixing bacteria or plants. Crop rotation and diversity can decrease the availability of certain resources to the weed community, and can select for different weed species over time (Entz et al. 1995; Le’ge’re and Samson 1999; Liebman et al. 1996). Liebman and Dyck (1993) suggested that a successful crop rotation for weed suppression must be diverse to create an unstable and inhospitable environment by reducing the availability of resources by varying the timing of weed management strategies. Buhler et al. (1997) suggested that
combining plant ecological knowledge with weed science could allow for weed management systems that take advantage of plant responses. A weed species might not be present in a field at high densities, even under favorable environmental conditions if effective weed management systems are implemented and resource availability for the weed is limited (Dale et al. 1992). However, a weed species can adapt to management tactics such as crop rotation, just as they can endure herbicides through developing resistance (Buhler et al. 1997). Persian darnel has adapted to the current weed management systems by developing resistance to ACC-ase inhibiting herbicides, surviving in water limiting environments due partially to a rapid life cycle, having a seed size similar to cereal, seed shattering with some seed retention on the spikelets, and non or misidentification as another grass weed or crop.

Doucet et al. (1999) conducted an extensive 10-yr crop rotation study to evaluate the impact of crop rotation and level of weed management on the weed community. The weed community is characterized by species evenness and richness. Weed community evenness and richness are defined as the relative proportion of weed species present and number of weed species present, respectively. The study determined that increasing crop diversity resulted in increased weed evenness and decreased weed richness compared to crop monoculture by varying seeding and harvest date, and using herbicides with different modes of action and selectivity. Le'ge're and Samson (1999) stressed the importance that crop rotation has in weed management by allowing herbicides of different modes of action and selectivity to be used and the ability to raise crops that are more competitive with certain weed species. Cropping sequence and diversity impact weed population dynamics by altering the pattern of
resource use by different crops, allelopathy, differences in tillage frequency and timing, and differences in herbicide mode of action and selectivity (Doucet et al. 1999; Entz et al. 1995; Le’ge’re and Samson 1999; and Liebman et al. 1996). Unfortunately, little work has documented the interference between weeds and different crops or crop types that might occur within a rotation. Therefore, little is known about crop rotation effects on weed species, except for the impact of different herbicides used in a cropping system on weed species. In the current study, we analyze the impact of crop on Persian darnel by rotating to crops other than spring wheat.

Allelopathy, or secondary plant metabolites and their degradation products are believed to suppress the growth of certain plant species. Allelopathic effects have been documented in the lab, but have not been clearly demonstrated in the field (Inderjit and Foy 2001). It has been suggested that crop root exudates can affect weed growth. Inderjit and Streibig (2001) found Italian ryegrass root length decreased with increased wheat seed density. Inderjit and Streibig (2001) concluded that wheat root exudates and or increased root interspecific interference for space decreased Italian ryegrass root length. Allelopathic effects of the crop might not occur until the year following growth. Studies have shown several crop residues to potentially decrease weed germination and growth (Crookston and Kurle 1989; Teasdale 1993). Implementation of crop rotations that have allelopathic effects on Persian darnel germination or emergence could increase control, in theory, if they can be identified.

A key goal of weed management is to decrease the weed seedbank. Crop rotations have shown conflicting results on the ability to decrease the weed seedbank of certain weed species. Ball (1992) found crop rotation to decrease the number and alter
the composition of weed species present in a natural seedbank compared to a monoculture system. The decrease in number and shift in the weed community seedbank was attributed to herbicide use. Buhler et al. (1997) suspected crop rotation decreased the weed seedbank by varying resource availability, allelopathy, soil disturbance, and weed management strategy.

Long-term Persian darnel management must rely on reducing its seedbank density. Seedbanks can be managed by exhausting seed reserves via germination, increasing seed mortality and minimizing seed production over time. Persian darnel seed is viable for up to 2 yr once buried in the soil (Banting and Gebhardt 1979). A weakness in the life strategy of Persian darnel might be the lack of long-term persistence in the weed seedbank. Crop rotations designed to impact Persian darnel seedbank and seed production could effectively control Persian darnel.

Crop Competition

Early research on crop-weed interference focused on the density and proximity of weeds relative to the crop and the influence of weeds on crop yield by reducing plant available resources (Clements et al. 1929). More recent research on crop-weed interference has focused on the mechanistic ability of a plant to compete with weeds (Kropff and Spitters 1991; McIntyre et al. 1997). Mechanistic factors that influence interspecific interference include crop and weed density, relative growth rates, time of emergence, rooting depth and architecture, canopy height and architecture, environment and spatial arrangement of individuals (McGiffen et al. 1997; Weaver et al. 1994; Radosevich 1987).
Pavlychenko and Harrington (1935) indicated plants that develop extensive rooting systems early in the growing season and acquired resources quickly and efficiently were more competitive. They also indicated the importance of understanding individual crop and weed rooting architecture to allow for selection of more competitive crop species. Choosing crops which root to different depths than targeted weeds can result in decreased interspecific interference and increased yield (McIntyre et al. 1997; Sheley and Larson 1995). Crop rooting depth is dependant upon plant morphology, genetics, soil type, and soil moisture potential (Gregory 1998). It is believed that Persian darnel has a very fine, fibrous, shallow root system, with a rooting depth similar to spring wheat (Dardanelli et al. 1997; Murphy and Smucker 1995; Stone et al. 1998). Spring wheat rooting depth ranges from 1 to 3 m depending on abiotic and biotic factors (Mishra et al. 1999). Canola rooting depth is approximately 1.5 to 2 m (Nielsen 1997). Sunflower rooting depth varies by cultivar and maturity length from 2 m (Jaafar et al. 1993) to 2.5 m (Dardanelli et al. 1997) for early maturing cultivars and 3 m (Dardanelli et al. 1997) for late maturing cultivars. These crops differ in rooting depth and structure, which might influence interference with Persian darnel. Research has indicated that under moisture limiting conditions differences in rooting depth might not be as critical to interference as water use efficiency (Anderson et al. 1999; McIntyre et al. 1997; Miller et al. 2000). Under moisture limiting conditions, water recharge might not be deep enough in the soil profile to allow for a competitive advantage of deeper rooting plants (McIntyre et al. 1997). As a result, plants gain a competitive advantage by capturing water faster than neighbors rather than avoiding competition by seeking water at different depths. The fibrous rooting system of Italian ryegrass, perennial
ryegrass, and potentially Persian darnel might provide the weed a competitive advantage in moisture limited environments dependent on growing season precipitation (Murphy and Smucker 1995; Stone et al. 1998). McIntyre et al. (1997) intercropped hedgerow trees with an annual crop of maize and cowpea (*Vigna sinensis* Endl.) in a study under dry conditions. Maize and cowpea yielded 50% less when grown with hedgerow trees than in monoculture. The decrease in yield was attributed to interspecific competition by the deep-rooted perennial hedgerow due to a lack of soil water recharge to deeper soil depths.

Plants compete for light aboveground by leaf area placement through canopy architecture, which impacts the amount of photosynthetic radiation that is available to their neighbors (Pavlychenko and Harrington 1935). Plant height and relative leaf area at the time of canopy closure can significantly influence the competitiveness of a plant (Cousens et al. 1991; Kropff and Spitters 1991). Accounting for the relative leaf area index of crop and weeds, at the time of crop emergence, has increased the predictive ability to model crop yield (Kropff and Spitters 1991; Kropff et al. 1992). Studies have shown that relative leaf area was a better predictor in estimating crop yield loss than weed density, since relative leaf area accounts for weed density and time of emergence (Kropff and Spitters 1991). Furthermore, accounting for the neighborhood canopy effects over the course of the growing season increases the predictive ability to quantify weed interference (Pike et al. 1990). Studies have found wild oat interference in wheat is caused by a reduction in wheat leaf area early in development and a reduction in light penetration to the crop canopy later in development (Cudney et al. 1991; Weaver et al. 1994). A greenhouse experiment conducted by Fischer et al. (2000) showed that barley
Hordeum vulgare L.) suppressed kochia (Kochia scoparia L.) growth more than spring wheat due to earlier and larger canopy development. Regnier and Stoller (1989) compared the interference between common cocklebur (Xanthium strumarium L.), jimsonweed (Datura stramonium L.), and velvetleaf (Abutilon theophrasti Medicus) with soybean (Glycine max Merill). Common cocklebur grew to the same height as soybean, whereas jimsonweed and velvetleaf grew below the crop canopy. A comparison of weed-soybean interspecific interferences showed common cocklebur had the greatest impact on crop yield. Common cocklebur’s greater competitiveness was attributed to its taller height and axillary growth. Persian darnel’s canopy development and height is less than spring wheat and canola. Sunflower develops a canopy limited in the ability to intercept light, several feet taller and later than Persian darnel. Therefore, differences in crop canopying architecture amongst the crops in this study might influence competition with Persian darnel because of differences in light environments associated with the different crops.

Interference changes over the course of the growing season with changes in nutrient availability as influenced by climate, irrigation or fertilization (Lutman et al. 1994; Patterson 1995). McGiffen et al. (1997) studied the interspecific interference of green foxtail (Setaria viridis) with corn in growing seasons with low and high precipitation. The study concluded corn yield was least affected by green foxtail during a growing season low in precipitation and that the relative competitiveness of corn increased during growing seasons high in precipitation. The competitiveness of corn was determined to be higher in wet years compared to dry years because green foxtail biomass was decreased greater with increased corn density during wet years than dry
years. High levels of late or early growing season moisture might reduce the impact of Persian darnel on crop yield.

A key factor that determines the outcome of interspecific interference is relative time of emergence (Harker et al. 2001; O'Donovan et al. 1985). Lutman et al. (1994) showed wild oat interference with canola (*Brassica rapa*) to increase when canola emergence was delayed 6 d more than wild oat. Later emerging weed cohorts have reduced fecundity and reduced impact on crop yield (Mickelson and Harvey 1999; Peters and Wilson 1983; Smith and Jordan 1993). Woolly cupgrass (*Eriochloa villosa* Thunb.) fecundity decreased with later emergence when grown in corn (Mickelson and Harvey 1999). A 7-day delay in emergence of sicklepod (*Cassia obtusifolia* L.) resulted in a 60% decrease in sicklepod stem dry weight, and reduced impact on crop yield when grown in soybean (Smith and Jordan 1993). California arrowhead (*Sagittaria montevidensis* Cham.) had been viewed as a severe weed problem in rice (*Oryza sativa* L.) for several years without knowing its impact on crop yield (Gibson et al. 2001). Unfortunately, due to high herbicide use, biotypes of California arrowhead have been confirmed to be resistant to the only selective herbicide available in rice. Gibson et al. (2001) found a density greater than 200-arrowhead plants/m² was required to decrease rice yield; and previous management levels were often not necessary to minimize yield loss. The low interspecific interference of arrowhead was attributed to late emergence and short growth height. The research conducted on arrowhead indicates the necessity to study the impact of Persian darnel on crop yield to determine the level of crop yield loss that Persian darnel might cause.
Crop seeding rate and seedling establishment are also important factors affecting crop-weed interference relationships. Increasing crop density from an established standard density in weed-free conditions can either reduce or have minimal impact on crop yield depending on the plasticity of the plant (Clarke et al. 1978; Grantham 1914; Martin et al. 2001; Morrison et al. 1990). Crop densities of 40,000 to 85,000 plants/ha did not affect sunflower yield. Increasing sunflower plant density increased test weight and oil content, and decreased mean seed weight and days to maturity in weed-free conditions (Holt and Campbell 1984). Morrison et al. (1990) measured canola yield under a range of seeding rates from 1.5 to 12.0 kg/ha, and found canola yield to be highest at seeding rates of 1.5 to 3.0 kg/ha under weed-free conditions. In similar weed-free studies, no yield response of canola was shown across seeding rates ranging from 3 to 12 kg/ha (Degenhardt and Kondra 1981). Under weed-infested conditions, increasing crop density can increase crop yield (Carlson and Hill 1985; Morrison et al. 1990; O’Donovan 1994). Carlson and Hill (1985) found spring wheat yield increased when the density of spring wheat was increased from 1,450,000 to 4,350,000 plants/ha when grown with wild oat. Increasing crop seeding rate can reduce weed fecundity (Ball et al. 1997; Pantone and Baker 1991). Canola competitiveness was decreased at densities less than 500,000 plants/ha with wild oat (Lutman et al. 1994), and reduce Tartary buckwheat (Fagopyrum tataricum L.) fecundity at densities greater than 2,000,000 plants/ha (O’Donovan 1994).

Decreasing crop row spacing has often been incorporated with increased crop seeding rate. Narrower row spacing can increase the competitiveness of the crop with weeds, but has not been as effective as increasing crop density (Blackshaw 1993;
Narrower row spacing has been more effective with crops that have incomplete canopies or canopy late in the growing season by reducing light penetration through the crop canopy earlier in the growing season. Canola yield increased with narrower row spacing under a constant seeding rate (Morrison et al. 1990). The increase in canola yield was attributed to a decrease in within-row intraspecific interference.

Crop cultivars differ in their competitiveness with weed interference (Bussan et al. 1997). In the absence of weed interference, semi-dwarf or short wheat cultivars have a higher yield potential than taller cultivars due to reduced lodging and increased carbon partitioning to the seed head (Balyan et al. 1991; Blackshaw 1994a). However, in the presence of weed interference, shorter cultivars can be less competitive than taller cultivars (Balyan et al. 1991; Blackshaw 1994a; Lanning et al. 1997). Another competitive difference between cultivars is their relative growth rates (Balyan et al. 1991). Balyan et al. (1991) found spring wheat cultivars with quicker growth development rates were more competitive with wild oat.

It has been suggested that weeds can also impact future crop yields through an increase in the soil weed seedbank and depletion of plant available nutrients during fallow periods (Kropff and Lotz 1992). Understanding weed resource use during fallow and the effects on future crop yield is essential in determining weed economic impact and developing a weed management plan (Auld et al. 1987). This study quantifies Persian darnel seed production in monoculture without an application of herbicide to determine Persian darnel seed production potential in an uncontrolled fallow period.
Research on Persian darnel biology and how it interferes with crops grown in the northern Great Plains is needed to understand its impact on crop development and yield. Understanding Persian darnel’s impact on crop development might indicate when interference is impacting crop yield. Understanding when and the amount of Persian darnel impact on the yield of alternative crops such as canola and sunflower as compared to spring wheat will aid in designing cropping systems that compete effectively with Persian darnel. Furthermore, understanding the effects of seeding rate on Persian darnel development and fecundity is needed to improve current management strategies. Evaluation and development of cultural management methods to control Persian darnel is essential for sustainable and economical weed management practices.
SPRING WHEAT, CANOLA, AND SUNFLOWER RESPONSE TO PERSIAN DARNEL (*LOLIUM PERSICUM*) INTERFERENCE

**Introduction**

Persian darnel (*Lolium persicum* Boiss. & Hoh.) is a cool season, C₃, annual monocot weed that has invaded cereal production fields of the northern Great Plains (NGP). The impact of Persian darnel on crop productivity has not been previously quantified. In a non-peer review report, Persian darnel was found to be as competitive with spring wheat (*Triticum aestivum* L.) as wild oat (*Avena fatua* L.) in dryland production systems (Hunter 1984). Preliminary, non-published, results indicate that Persian darnel at 30 plants/m² reduced spring wheat yield by 15% (Hunter 1984). Persian darnel densities exceeding 2,800 plants/m² were quantified in dryland wheat production (Hunter 1984). Persian darnel is primarily managed through application of selective grass herbicides at an approximate cost of $30.00/ha, even though its yield impact has not been quantified (Hunter 1995; USDA 2000). Preliminary results suggest that a better understanding of the competitive relationships between Persian darnel and crops commonly grown in the NGP could increase the efficiency of weed management and encourage integrated weed management systems.

Acreage infested by Persian darnel has increased throughout much of the NGP (MSU Herbarium 1998; Wilderness Invaders Project 2002). Speculations suggest that Persian darnel has spread because it has a life cycle similar to spring wheat, poor
management systems, and resistance to selective graminicides used in cereal production (Weed Science Organization 2000). Banting and Gebhart (1979) determined that Persian darnel germinated at temperatures from 5 to 26 C similar to spring wheat and wild oat (Fennimore et al. 1998; Wuest et al. 1999). Thus suggesting that Persian darnel, spring wheat and wild oat emerge at similar times in the spring of the year. Previous research documented that weeds emerging prior to or at the same time as the crop have larger impacts on yield relative to later emerging weeds (Lutman et al. 1994; Knezevic et al. 1997). Persian darnel has the potential to have a significant yield impact on spring seeded crops through its ability to germinate and emerge during cool soil conditions and by capturing resources prior to crop establishment.

Integrated weed management systems that incorporate the use of diverse crop rotations have been found to effectively manage annual grass weeds within dryland wheat production systems (Blackshaw 1994b; Derksen et al. 2002; Lyon and Baltensperger 1995; Wicks 1984; Young et al. 1996). The population density of downy brome (Bromus tectorum L.) decreased more in winter wheat rotations with canola (Brassica napus Koch.), field pea (Pisum sativum L.), corn (Zea mays L.), soybean (Glycine max Merill), sorghum (Sorghum bicolor L.) or prosomillet (Panicum miliaceum L.) than when grown in a continuous or fallow rotation (Blackshaw 1994b; Wicks 1984; Young et al. 1996). Similarly, wild oat population densities declined more rapidly under winter wheat rotations with field pea and barley (Hordeum vulgare L.) than when grown in a continuous rotation (Young et al. 1996). Broadleaf crops in rotation with cereal crops in the NGP have the potential to diminish Persian darnel
interference and future densities due to increased crop competition and increased herbicide options.

Crop rotations effective at managing weed populations must be diverse enough to create an unstable and inhospitable environment for weed populations (Liebman and Dyck 1993). Crop diversity, the associated diversity of crop husbandry practices and the sequence in which crops are grown can reduce weed interference and fecundity through several mechanisms including differential resource use, allelopathic effects, and an increase or decrease in soil disturbance. Unfortunately, little work has documented the interference between weeds and different crops or crop types that might occur within a rotation. Research on crop rotations generally only document the impact of various herbicidal control measures and the impact of different crops on weed population dynamics (Derksen et al. 2002; Doucet et al. 1999; Le`ge`re and Samson 1999).

Interest in producing alternative crops has increased in the northern Great Plains over the past decade. Alternative crops include canola, sunflower (*Helianthus annuus* L.), safflower (*Carthamus tinctorius* L.), chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.), field pea and flax (*Linum usitatissimum* L.) (National Agricultural Statistics Service 2001). Canola and sunflower differ in agronomic production practices such as planting density, fertilizer requirements, seeding period, and harvest timing compared to spring wheat (Carlson and Hill 1985; Holt and Campbell 1984; Morrison et al. 1990; Thomas 1984). For example, increasing crop density increased crop yield in the presence of weed interference (Carlson and Hill 1985; O’Donovan 1994). In addition, canola and sunflower utilize resources in a different pattern than spring wheat.
Sunflower tends to root deeper than spring wheat or canola, suggesting different patterns of resource consumption from the soil (Dardanelli et al. 1997; Jaafar et al. 1993; Nielsen 1997). In contrast, canola has a faster, denser crop canopy development than spring wheat allowing less light penetration below the crop canopy (Morrison et al. 1990).

Differences in resource consumption and agronomic production practices will likely result in differences in how Persian darnel impacts each crops respective yield. Unfortunately, little research has been conducted to quantify the impact of Persian darnel interference on spring wheat, sunflower, or canola yield. The goal of this research was to quantify the effects of Persian darnel interference on spring wheat, canola and sunflower yield and yield components over a range of crop and weed densities. Based on previous spring wheat research (Fischer et al. 2000; Lanning et al. 1997; Mishra et al. 1999), we hypothesized that canola and sunflower might be able to tolerate Persian darnel interference more than wheat. We also hypothesize, that increasing the seeding rate of spring wheat, canola and sunflower can decrease the yield impact of Persian darnel on the respective crops. We evaluated both crop density and crop seeding rate effects on crop yield over a range of Persian darnel densities because higher crop densities might not necessarily be obtained with increased crop seeding rate.

Materials and Methods

Experimental Procedures
Field experiments were conducted in 2000 and 2001 at the Montana State University (MSU), Arthur Post Research Center near Bozeman, MT (latitude: 45° 47' N, longitude 111° 9' W). The soil type was an Amsterdam silty clay loam (fine-silty, mixed, superactive, frigid typic haplustolls, 0 to 4% slopes) composed of 12% sand, 53% silt, 33% clay, with 2% organic matter and pH of 7.4. The 50-yr average rainfall was 42 cm/yr and the study site has been under conventional tillage for at least 25 years (Table 7, Appendix B). Spring wheat was the previous crop for each year of the study.

The experimental design was a randomized complete block, with a split-plot treatment arrangement and with three replications. The whole plot factor was crop type (spring wheat, canola, and sunflower). The subplot treatment factors were three crop seeding rates (1X, 1.5X and 2X of the recommended seeding rates) and Persian darnel seeding rates in a factorial arrangement.

Persian darnel seeding rates were determined from the previous year natural seed rain in 2000 and 2001, and supplemental Persian darnel seed was spread the fall prior to the 2001 experiment. Persian darnel natural seed rain was recorded in permanently marked plots the previous fall to determine seeding rates for the experiments. Persian darnel seed rates for the 2000 experiment ranged from 0 to 12,000 seed/m². In preparation for the 2001 trial, spring seeded Persian darnel failed to produce seed thus requiring supplemental seeding in the fall. Supplemental Persian darnel seed was spread into permanently marked plots at densities of 0, 170, 230, 280, 550, 870, 2,150, 4,150 and 6,150 seeds/m² in the fall prior to the 2001 growing season. Supplemental seed was harvested from Persian darnel growing in monoculture plots within the 2000 experiment.
The site was tilled in the spring with a disk and field cultivator prior to fertilizer application. All plots were fertilized with 336 kg/ha of 25-5-8 as N-P-K. Canola plots received an additional 112 kg/ha of ammonium sulfate (10-0-0-20). Fertilizer rates were determined from soil test results and Montana State University recommendations. Fertilizer was broadcast on the soil surface with a granular applicator and incorporated with a field cultivator prior to seeding. The targeted 1X crop seeding densities were 123, 60 and 3 plants/m² for spring wheat, canola and sunflower, respectively. The 1X crop seeding rates were 191, 190 and 4 seed/m² for spring wheat, canola and sunflower, respectively. Viability of crop seed lots was tested before planting and seeding rates were adjusted accordingly. All crops were seeded with a double disc, cone distance-displacement plot seeder with rows spaced 25.4 cm apart. Sunflower seed can bridge in seed tubes of conical seeders, restricting flow of seed to the seeder opener, resulting in uneven seed placement. Therefore, sunflower was seeded at two to four times the targeted plant density and hand thinned to obtain a uniform stand of equidistantly spaced plants at the desired densities.

‘McNeil’ spring wheat and ‘Hyola 308’ canola were seeded 3.8 and 1.3 cm deep, respectively on 8 April 2000 and on 17 April 2001. Spring wheat and canola were seeded as soon as the soil was sufficiently dry to bear machinery traffic. Sunflower (‘Cenex 803’) has a low frost tolerance relative to spring wheat and canola and was seeded later on 16 May 2000 and on 19 May 2001. Sunflower seeding was preceded by an application of glyphosate plus ammonium sulfate at 0.42 kg ae/ha and 1.9 kg/ha to control the first cohort of weeds, a common practice in the northern Great
Plains. All plots were maintained free of all weeds except Persian darnel by hand weeding throughout the growing season.

In 2000, canola seed was treated with benomyl, a fungicide, but a flea beetle (*Phyllotreta crucisere*) infestation occurred within the study. Therefore in 2001, canola seed was treated with benomyl plus imidacloprid, a systemic insecticide and fungicide, for control of flea beetle and effects of potential disease. The entire study was treated with lambda-cyhalothrin to control escaped flea beetle or sunflower beetle (*Zygograma exclamationis*) populations both years. Spring wheat seed was treated with tebuconazole and imazalil, and sunflower seed was treated with metalaxyl and fludioxonil each year to reduce the potential effects of plant disease.

Data Collection

Crop and Persian darnel density, crop yield and crop yield component data were collected from 0.25 m$^2$ circular quadrats in each subplot. Three and four quadrats per subplot were established immediately following seeding in 2000 and 2001, respectively. Subsampling was increased from 3 to 4 quadrats in 2001 to improve coefficient of determination. Quadrats were located randomly with the restriction that they be at least 30 cm from the plot edge to reduce edge effects. Spring wheat, canola and Persian darnel seedlings were counted in each quadrat on May 20, 2000, and on May 29, 2001, when spring wheat reached the three-leaf stage (Zadock’s scale 1.3). Sunflower seedling density was determined 3 wk after seeding by hand thinning to the desired plant densities, when the majority of the sunflower plants had emerged. Sunflowers that emerged after 3 wk were removed.
Crop plants were hand harvested at maturity. Spring wheat was harvested on July 30, 2000 and August 20, 2001, canola was harvested on July 26, 2000 and August 12, 2001, and sunflower was harvested September 15, 2000 and September 8, 2001. Mesh bags were placed on sunflower plants to prevent yield loss from herbivore predation. Crop maturity was determined by plant color and seed moisture content. Individual plants were separated and counted within each quadrat. Yield components measured for spring wheat included: seed production (seed/plant), tiller production (tillers/plant), seed produced per tiller (seed/tiller), and seed weight (g/seed). The yield components measured for canola included: seed production (seed/plant), branch production (branches/plant), pod production (pods/branch), seed produced per pod (seed/pod) and seed weight (g/seed). Yield components measured for sunflower included: seed production (seed/plant) and seed weight (g/seed). Crop yield (kg/ha) and seed production (seed/plant) were determined in the lab. Final yield was determined by 1) removing all foreign material, 2) determining the seed weight of a 1,000 seed sub sample and 3) quantifying the total weight of the harvested crop from each quadrat.

Statistical Analysis

Relationships Between Crop and Weed Density on Crop Yield. Nonlinear regression was used to relate crop and weed density to crop yield (kg/ha). Data for each year and data combined across years was fit to a crop yield model (Jasieniuk et al. 2001) (Hooke-Jeeves Pattern Moves estimation procedure; StatSoft Inc. 2000) (Equation 1).
\[ Y = \left[ \frac{j \cdot N_c}{1 + j \cdot N_c / Y_{\text{max}}} \right] \cdot \left[ 1 - \left( \frac{i \cdot N_w}{1 + i \cdot N_w / a} \right) \right] \]  

\( Y \) was crop yield (kg/ha), \( j \) was crop yield per crop seedling as crop density approached zero, \( N_c \) was crop seedling density (plants/m²), \( Y_{\text{max}} \) was the maximum crop yield observed (kg/ha), \( i \) was the proportional yield loss per unit weed density as weed density approached zero, \( N_w \) was Persian darnel seedling density (plants/m²), and \( a \) was the proportional yield loss as Persian darnel density approached infinity. Sunflower was related to Persian darnel density prior to glyphosate application and after glyphosate application separately. Regression residuals were analyzed using a runs test for randomness, Levene’s test for constancy of variance, and a goodness of fit test for normality of error terms (Neter et al. 1996). Parameter estimates were tested for significance at the P \(< 0.05\).

**Crop Competitiveness.** Estimates of parameters \( i \) and \( a \) from Equation 1 were compared among spring wheat, canola and sunflower to determine the relative effect Persian darnel had on each crop. Bonferroni confidence intervals were used to compare estimates of \( i \) and \( a \) for each crop within each year. Differences in parameter estimates were tested for significance at P \(< 0.05\).

**Persian Darnel Impact on Seed Production per Plant.**

Nonlinear regression was used to relate Persian darnel and crop density to seed production per plant (seed/plant) for each crop. Seed production per plant was related
to crop density using a nonlinear regression model each year (Firbank and Watkinson 1985) (Hooke-Jeeves Pattern Moves estimation procedure; StatSoft Inc. 2000) (Equation 2).

\[
W_A = W_{md}(1 + Q_A(N_c + CN_w))^{-b_A}
\]  

\[W_A\] was the mean number of seed produced per crop plant, \(W_{md}\) was the maximum observed number of seed produced per crop plant, \(Q\) was the area (m\(^2\)) required by a plant to achieve a seed yield of \(W_{md}\), \(C\) was the competition coefficient, and \(b\) described the resource utilization efficiency of the population. Parameter \(b\) was not different than \(-1\), indicating compliance with the reciprocal yield law, and therefore was set at \(-1\) for the analysis (Firbank and Watkinson 1985). Parameter estimates were tested for significance at the \(P \leq 0.05\).

**Persian Darnel Impact on Individual Crop Yield Components.**

Step-wise multiple linear regression was used to relate Persian darnel and crop density to crop yield components using the following equation (Equation 3).

\[
y = \beta_0 + \beta_1 N_c + \beta_2 N_w + \epsilon
\]  

\(y\) was the crop yield components. Spring wheat yield components included: tiller production (tiller/plant), seed produced per tiller, and seed weight (g/seed). Canola yield components included: branch production (branches/plant), pod production
(pods/branch), seed produced per pod, and seed weight (g/seed). Sunflower yield components included seed weight (g/seed). Other model parameters were $\beta_0$, the intercept; $\beta_1$, the change in crop yield component with a change in crop density; $\beta_2$, the change in crop yield component with a change in Persian darnel density, and $\epsilon$ was an estimated error term. An interaction of crop and Persian darnel density on crop yield components was also tested. Regression equations and parameter estimates were tested for significance at the $P \leq 0.05$.

Effect of Crop Seeding Rate on Crop Yield. The effect of crop seeding rate on crop yield was tested to determine if increasing crop seeding rate impacted crop yield. The effect of crop seeding rate on crop yield was determined using either analysis of covariance or nonlinear regression. Analysis of covariance, with Persian darnel density as a covariate, was used to test for differences among means if it was determined from Equation 1 that Persian darnel density did not affect crop yield. If Persian darnel density reduced crop yield as determined by Equation 1, then nonlinear regression was performed using a rectangular hyperbolic function to quantify the effect of seeding rate on the relationship between crop yield and Persian darnel density (Cousens 1985b) (Equation 4).

\[
Y = Y_{\text{max}} \cdot \left[1 - \frac{i^*N_w}{(1 + i^*N_w/a)}\right]
\]
$Y_{\text{max}}$ was the maximum crop yield within a seeding rate. An increase in crop yield from crop seeding rate was determined using an F-test and comparing parameter estimates (Neter et al. 1996). F-tests were determined significant at $P \leq 0.05$.

**Crop Seedling Density Response to Crop Seeding Rate.** Linear regression was used to relate established crop density to crop seeding rate to determine if increasing crop seeding rate increased crop density (Equation 5).

$$N_c = \beta_0 + \beta_1 X_c + \epsilon$$  \hspace{1cm} [5]

$\beta_0$ was the intercept, $\beta_1$ was the change in seedling density with the change in crop seeding rate, $X_c$ was the crop seeding rate, and $\epsilon$ was an estimated error term. Regression F-tests were tested for significance at the $P \leq 0.05$. The effect of crop seeding rate on sunflower density was not tested because sunflower was over-seeded, then hand thinned to the target densities.

**Results and Discussion**

**Relationship Between Crop and Weed Density on Crop Yield**

Crop yields varied across years as typically occurs within production systems of wheat, canola and sunflower (data not shown). In part, the variability in crop yield was due to differences in crop seedling density, Persian darnel seedling density, and the
climatic conditions that occurred in 2000 and 2001 (Table 7 and Figure 21, Appendix B).

The per plant crop yield at low crop density, parameter $j$, was determined for all crops across both years, except for canola in 2000 (Table 1). The inability to quantify the per plant yield at low density in canola in 2000 was likely due to an insufficient number of observations at low crop densities. Intuitively, crop yield will increase with density prior to the impacts of intraspecific competition (Cousens 1985b; Morrison et al. 1990). The presence of weeds might increase the crop yield response to crop density when weeds interfere with crop growth and development. Other studies have repeatedly shown increases in crop yield with increasing crop density in the presence of weed interference (O’Donovan 1994; Weiner et al. 2001). Per plant yield per seedling only varied across years within sunflower (Table 1).

The yield impact of Persian darnel at low weed density, parameter $i$, was fit to the combined year data set of spring wheat, and the 2000, 2001 and combined year data set of canola (Table 1). The inability to fit $i$ might be due to the lack of yield response to Persian darnel interference, high amount of variability associated with crop yield at low weed densities, or an insufficient number of observations at low weed densities to allow for quantification of the parameter (Cousens 1985a, 1985b; Jasieniuk et al. 2001). Sunflower yield varied with the Persian darnel density prior to glyphosate application in 2000, 2001 and the combined year data set, but did not vary with Persian darnel density 3 WAP in 2000. Therefore, the data presented for sunflower yield response was related to Persian darnel density prior to glyphosate application. In part, the differences in Persian darnel density effects might be due to a wider range in Persian darnel densities
prior to seeding sunflower than after, or simply that Persian darnel had a larger impact on resources (likely water and or soil nutrients) prior to seeding sunflower than after (Holman 2002, chapter 3). The first cohort of Persian darnel was allowed to grow uncontrolled for several weeks, which likely reduced resource availability for sunflower initial growth and development. This suggests that Persian darnel affected crop yield early in the growing season especially sunflower.

The maximum impact of Persian darnel on crop yield, parameter $a$, was fit to all crops and years except for the 2000 data set of spring wheat and the 2000 and combined year data set of sunflower (Table I and Figure 4). The inability to fit $a$ suggests that either Persian darnel did not affect spring wheat or sunflower yield in 2000 or that there was insufficient data observations to quantify parameter $a$. The inability to detect Persian darnel impacts on spring wheat and sunflower yield in 2000 was confirmed using linear regression (Table 13, Appendix E), this indicates that Persian darnel did not affect crop yield due to lower weed densities in 2000 compared to 2001. The inability to fit $a$ to the combined data set of sunflower might be due to differences in $a$ between years.

Differences in climatic conditions, seed dormancy and seed viability across years likely influenced the germination and subsequent emergence of crop and Persian darnel seedlings, partly explaining the difference in densities across years. Persian darnel densities were higher in 2001 than 2000 likely due to more precipitation occurring immediately after final tillage and seeding. Banting and Gebhart (1979) concluded that Persian darnel seed stored under moist, cool soil conditions afterripened and germinated quicker and at a higher rate than seed stored under dry conditions. In
2001, 0.90 cm of precipitation occurred within 4 d after seeding spring wheat and canola compared to no precipitation for 1 wk after seeding in 2000. As a result the potential for higher yield impacts due to Persian darnel in 2001 existed due to higher overall densities.

In addition to impacts on crop and Persian darnel seedling density, climatic conditions also likely influenced the relationships between density and final yield. Moisture is a major limiting resource to crop productivity in the NGP (Miller et al. 2001), and changes in water availability (precipitation) changes the response of crop yield to crop density and the impact of weeds on crop (Patterson 1995). Total growing season plant available water (plant available water at planting + precipitation) was higher in 2000 than 2001. Plant available moisture at planting was estimated at 12.19 and 9.17 cm in 2000 and 2001, respectively using a Paul-Brown moisture probe (Brown 1960). In 2000, precipitation occurred throughout the growing season. In contrast, in 2001 precipitation was minimal throughout the growing season, except for high precipitation occurrence the middle of June (Table 7 and Figure 21, Appendix B). Assuming water is the primary resource each species is competing for, the impact of Persian darnel on each crop should be more severe in 2001 due to increased water stress on the crop early in the growing season. \( Y_{max} \) was higher in 2001 compared to 2000. \( Y_{max} \) might have been higher in 2001 because \( Y_{max} \) was derived from plots low in crop and weed density, hence low in inter and intraspecific interference for resources early in the growing season. Also, the high precipitation occurrence in June of 2001 might have increased crop seed production and seed weight.
The combined year data set analysis often decreased the parameter standard errors and increased the number of parameters fit to the model because more observations were used to fit the model (Table 1 and Figure 4). Higher Persian darnel densities and increased observations in the 2001 data set allowed for better estimation of parameter $a$. Persian darnel density reached 354 and 980 seedlings/m$^2$ in canola, and
Table 1. Spring wheat, canola and sunflower yield response to crop and Persian darnel density. Parameter estimates derived from nonlinear rectangular hyperbolic model (Equation 1). The model was fit by year and to data combined across years. Parameter estimates were compared individually by year.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>Y max (kg/ha)</th>
<th>$j^a (SE)$</th>
<th>$i^a (SE)$</th>
<th>Comparison of $i^b$</th>
<th>$a^a (SE)$</th>
<th>Comparison of $a^b$</th>
<th>$R^2$</th>
<th>$n$</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>2000</td>
<td>5212</td>
<td>50.26 (8.48)</td>
<td>0.000 (0.001)</td>
<td>a</td>
<td>0.15 (0.49)</td>
<td>a</td>
<td>0.20</td>
<td>76</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>6036</td>
<td>53.51 (8.05)</td>
<td>0.001 (0.001)</td>
<td>x</td>
<td>0.82 (0.41)</td>
<td>y</td>
<td>0.32</td>
<td>141</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>Years Combined</td>
<td>6036</td>
<td>51.10 (6.17)</td>
<td>0.001 (0.001)</td>
<td>-</td>
<td>0.83 (0.45)</td>
<td>-</td>
<td>0.23</td>
<td>220</td>
<td>32</td>
</tr>
<tr>
<td>Canola</td>
<td>2000</td>
<td>2738</td>
<td>147.12 (140.82)</td>
<td>0.031 (0.025)</td>
<td>a</td>
<td>0.61 (0.09)</td>
<td>a</td>
<td>0.32</td>
<td>80</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>4296</td>
<td>31.12 (3.44)</td>
<td>0.002 (0.001)</td>
<td>x</td>
<td>0.85 (0.22)</td>
<td>y</td>
<td>0.37</td>
<td>144</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>Years Combined</td>
<td>4296</td>
<td>25.76 (2.00)</td>
<td>0.002 (0.001)</td>
<td>-</td>
<td>0.70 (0.19)</td>
<td>-</td>
<td>0.29</td>
<td>225</td>
<td>45</td>
</tr>
<tr>
<td>Sunflower</td>
<td>2000</td>
<td>4477</td>
<td>1435.00 (252.87)</td>
<td>0.001 (0.001)</td>
<td>a</td>
<td>0.34 (0.14)</td>
<td>a</td>
<td>0.40</td>
<td>81</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>6578</td>
<td>938.21 (157.73)</td>
<td>0.001 (0.001)</td>
<td>x</td>
<td>0.51 (0.16)</td>
<td>x</td>
<td>0.33</td>
<td>143</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>Years Combined</td>
<td>6578</td>
<td>921.63 (187.38)</td>
<td>0.001 (0.001)</td>
<td>-</td>
<td>0.57 (0.36)</td>
<td>-</td>
<td>0.37</td>
<td>224</td>
<td>64</td>
</tr>
</tbody>
</table>

$a$ Parameter estimates fit to crop yield model (Equation 1): $j$, yield as crop density approaches zero; $i$, proportional yield loss as Persian darnel density approaches zero; $a$, proportional yield loss as Persian darnel density approaches infinity.

$b$ Parameter estimates compared by year. Letter set for (a) for 2000 and (x-y) for 2001.
Figure 4. Effects of crop and Persian darnel density on crop yield. Data were combined across years and fitted to Equation 1. Parameter estimates and regression statistics are shown in Table 1.
728 and 2,328 seedlings/m² in spring wheat in 2000 and 2001, respectively (data not shown).

**Crop Competitiveness**

The parameter estimates predicting crop yield were compared to assess which crop was impacted most by Persian darnel. Crops did not differ in the impact of Persian darnel at low weed densities, parameter \(i\), across either year (Table 1). The maximum impact of Persian darnel on yield, parameter \(a\), did not differ across crops in 2000 even though it ranged from 0.15 (15% in wheat) to over 0.60 (60% in canola). In contrast, Persian darnel had a greater effect on the yield of spring wheat and canola than it did on sunflower in 2001. Maximum yield loss caused by Persian darnel was 51% in sunflower as compared to over 80% in spring wheat and canola in 2001 (Table 1). Differences in \(i\) or \(a\) were often unable to be detected due to large standard errors associated with the parameter estimates. These results suggest that Persian darnel interference had the least impact on sunflower yield compared to spring wheat and canola. Reduced interference in sunflower was likely due to delayed seeding which allowed a pre-plant application of glyphosate to remove the initial cohort of emerged Persian darnel seedlings and reduce the duration of interference as well as the overall density of Persian darnel growing within the crop. The later emerging cohort of Persian darnel seedlings that interfered with sunflower was not growing during its optimal growing season, and therefore might have been less competitive with sunflower. Furthermore, sunflower rooted deeper than Persian darnel, which might have decreased
Persian darnel interference due to niche differentiation (Figure 23, Appendix D; Sheley and Larson 1995).

**Persian Darnel Impact on Seed Production per Plant.**

The level of intra and interspecific interference of crop and Persian darnel density can partially be explained by their influence on seed production per plant. This analysis evaluated the area required for an individual crop plant to obtain maximum seed production per plant (parameter $Q$), the competitive indices of crop and weed on seed production per plant (parameter $C$), and the ability of the crop to compensate for the effects of increasing crop density (parameter $b$) (Firbank and Watkinson 1985). In both years, the effect of intraspecific interference was greater than the effect of interspecific interference on crop seed production per plant; as indicated by the competition coefficient (parameter $C$) being less than 1 (Firbank and Watkinson 1985) (Table 2). In 2000, Persian darnel reduced canola seed production per plant, but an impact on spring wheat or sunflower seed production per plant was not detected as indicated by parameter $C$ (Table 2). The results from canola, in 2000, suggest that each Persian darnel seedling had an effect 0.75 of 1 canola seedling on per plant seed production. In 2001, Persian darnel reduced seed production per plant of all crops (Table 2). The larger effect of Persian darnel on crop seed production in 2001 compared to 2000 might be associated with less growing season precipitation early in the growing season in 2001 and higher weed densities in 2001. In 2001, the results suggest that Persian darnel had an effect of 0.36 of 1 spring wheat plant, 0.58 of 1 canola plant, and 0.004 of 1 sunflower plant on per plant seed production. These results
indicate that Persian darnel had the least effect on sunflower seed production compared to spring wheat and canola in each year (Table 2).

The ability of a crop to tolerate increasing plant density or intraspecific interference was indicated by parameter b, and was not different amongst crop in either year (data not shown). Parameter b, when estimated by the model was not different than 1, and therefore was set at 1 (Firbank and Watkinson 1985).

These results are similar to the findings relating crop and weed density to final crop yield (Table 1). Where an effect of Persian darnel on spring wheat and sunflower yield or seed production was unable to be detected, and that Persian darnel is impacting sunflower yield and seed production the least. However, these results suggest that intraspecific interference is having a greater impact on crop yield than interspecific interference.

Table 2. Spring wheat, canola and sunflower seed production per plant response to crop and Persian darnel density. Parameter estimates derived from nonlinear yield per plant model (Equation 2).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>( w_{ad} )^a</th>
<th>( Q ) ( ^a ) (SE)</th>
<th>( C ) ( ^a ) (SE)</th>
<th>( R^2 )</th>
<th>n</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>2000</td>
<td>100</td>
<td>0.004 (0.000)</td>
<td>0.040 (0.097)</td>
<td>0.30</td>
<td>80</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>100</td>
<td>0.005 (0.000)</td>
<td>0.364 (0.085)</td>
<td>0.43</td>
<td>144</td>
<td>53</td>
</tr>
<tr>
<td>Canola</td>
<td>2000</td>
<td>2000</td>
<td>0.016 (0.002)</td>
<td>0.746 (0.312)</td>
<td>0.44</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>1166</td>
<td>0.007 (0.001)</td>
<td>0.577 (0.133)</td>
<td>0.34</td>
<td>144</td>
<td>36</td>
</tr>
<tr>
<td>Sunflower</td>
<td>2000</td>
<td>3360</td>
<td>0.265 (0.021)</td>
<td>0.001 (0.001)</td>
<td>0.39</td>
<td>80</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>2000</td>
<td>0.122 (0.009)</td>
<td>0.004 (0.001)</td>
<td>0.38</td>
<td>144</td>
<td>43</td>
</tr>
</tbody>
</table>

^a Parameter estimates fit to yield per plant model (Equation 2): \( w_{ad} \), represents the maximum seed produced per plant; \( Q \), represents the area required by a plant to achieve its maximum yield potential; and \( C \), is the competition coefficient.
The results of this analysis can also suggest the area necessary for each crop to maximize its per plant yield in the absence of Persian darnel interference as indicated by parameter $Q$ (Table 2). Spring wheat required 0.004 m$^2$ in 2000 and 0.005 m$^2$ in 2001, canola required 0.016 m$^2$ in 2000 and 0.007 m$^2$ in 2001, while sunflower required 0.27 m$^2$ in 2000 and 0.12 m$^2$ in 2001 to obtain maximum seed production per plant. The area required by each crop corresponds with the recommended planting density for these crop types, with sunflower having the lowest planting density and spring wheat having the highest (Carlson and Hill 1985; Degenhardt and Kondra 1981; Holt and Campbell 1984).

Persian Darnel Impacts on Individual Crop Yield Components.

An interaction of crop and Persian darnel density on crop yield components was tested, but was insignificant for all regressions so data is not reported. Persian darnel had no effect on spring wheat yield components in 2000, as Persian darnel did not influence yield or seed produced per plant in 2000. In 2000, increasing spring wheat density reduced spring wheat tillering, suggesting intraspecific interference affected spring wheat development more than interspecific interference. In 2001, increasing Persian darnel and spring wheat density reduced spring wheat tiller production and seed production per tiller, but did not affect seed weight (Table 3 and Figure 5). This suggests the impact of Persian darnel on spring wheat yield and seed production per plant was largely due to its impact on spring wheat tillering and seed production per tiller. Tillering initiates when spring wheat is at the 2 to 3 leaf stage of development (Zadocks 2.0-3.0), and seed production initiates at the 4 leaf stage (Zadocks 3.1)
Previous research has documented that intra and interspecific interference have influenced tillering and seed production of wheat (Donald and Khan 1996; Knezevic et al. 1997). Donald and Khan (1996) found Canadian thistle (*Cirsium arvense* L.) also impacted wheat tillering and seed production per tiller, but did not affect seed weight. They concluded that Canadian thistle primarily reduced wheat yield by reducing plant available water. Future research should attempt to document the impact of Persian darnel on spring wheat development early in the growing season to develop a better understanding of the mechanism of competition, in particular how Persian darnel can impact tillering.

Increasing Persian darnel and crop density reduced canola pod per branch in 2000, but did not affect seed per pod, branch per plant, or seed weight (Table 3 and Figure 6). In 2001, Persian darnel reduced canola branch per plant, pod per branch and seed per pod (Table 3 and Figures 6 and 7). In 2001, increasing canola density reduced branch per plant, pod per branch, but did not affect seed per pod or seed weight. Branch initiation by canola occurs after axially bud formation (BBCH 21), whereas pod formation is indeterminate initiating at flowering (BBCH 50) and continuing until resources become limiting (Lancashire et al. 1991; Thomas 1984). Previous research has shown pod formation and seed fill to be highly dependent upon rapid development and large growth of the leaf area, and reduced with a lack of resources (Thomas 1984). Thomas (1984) indicated branching and pod production can be negatively correlated with a decrease in carbohydrates, nutrients, light and moisture. Persian darnel could impact resource availability (nutrient, light and moisture) and stress canola during...
branch or pod formation leading to a decrease in yield. Future research should focus on the mechanism exploring how Persian darnel impacts canola.

Persian darnel had no effect on the seed weight of sunflower in either year (Table 3). In 2001, increasing crop density reduced sunflower seed weight, again suggesting intraspecific interference affected crop growth more than interspecific interference.

These results indicate that Persian darnel affected the yield of all crops early in plant development by reducing seed production and not affecting seed weight. The results of this research are similar to the results found by Stone et al. (1998) who measured the effect of Italian ryegrass (*Lolium multiflorum* Lam.) on winter wheat vegetative and reproductive components. Their results concluded that Italian ryegrass affected wheat during vegetative growth and early in reproductive growth, but not during seed fill. They concluded that interference occurred primarily through belowground competition. Increasing crop density could potentially increase the number of tillers, branches, and pods per unit area. In part this might explain why crop yields were higher when crop density was higher. More spring wheat plants increased the tiller density and more canola plants increased the branch and pod density thereby offsetting the negative yield impacts of Persian darnel.
Table 3. Parameter estimates for data fitted to Equation 2, showing the effects of Persian darnel density on spring wheat, canola, and sunflower yield components.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>Yield Component</th>
<th>$B_0$ ^a (SE)^b</th>
<th>$B_1$ (SE)</th>
<th>$B_2$ (SE)</th>
<th>$R^2$</th>
<th>n</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spring wheat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>tiller/plant</td>
<td>4.234 (0.226)</td>
<td>-0.009 (0.001)</td>
<td>NS</td>
<td>0.58</td>
<td>80</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed/tiller</td>
<td>23.963 (1.810)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed weight</td>
<td>0.028 (0.002)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>tiller/plant</td>
<td>2.793 (0.149)</td>
<td>-0.003 (0.000)</td>
<td>-0.001 (0.003)</td>
<td>0.27</td>
<td>144</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed/tiller</td>
<td>29.343 (1.289)</td>
<td>-0.032 (0.005)</td>
<td>-0.010 (0.002)</td>
<td>0.38</td>
<td>144</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed weight</td>
<td>0.040 (0.001)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>144</td>
<td>97</td>
</tr>
<tr>
<td><strong>Canola</strong></td>
<td>2000</td>
<td>branch/plant</td>
<td>2.126 (0.217)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pod/branch</td>
<td>16.112 (1.362)</td>
<td>-0.015 (0.007)</td>
<td>-0.003 (0.022)</td>
<td>0.07</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed/pod</td>
<td>17.708 (1.194)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed weight</td>
<td>0.002 (0.000)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>branch/plant</td>
<td>2.756 (0.15)</td>
<td>-0.004 (0.001)</td>
<td>-0.002 (0.000)</td>
<td>0.20</td>
<td>144</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pod/branch</td>
<td>11.579 (0.918)</td>
<td>-0.013 (0.005)</td>
<td>-0.006 (0.003)</td>
<td>0.19</td>
<td>144</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed/pod</td>
<td>20.818 (1.115)</td>
<td>NS</td>
<td>-0.008 (0.003)</td>
<td>0.10</td>
<td>144</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>seed weight</td>
<td>0.003 (0.000)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>144</td>
<td>4</td>
</tr>
<tr>
<td><strong>Sunflower</strong></td>
<td>2000</td>
<td>seed weight</td>
<td>0.035 (0.003)</td>
<td>NS</td>
<td>NS</td>
<td>-</td>
<td>80</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>seed weight</td>
<td>0.047 (0.002)</td>
<td>-0.001 (0.000)</td>
<td>NS</td>
<td>0.10</td>
<td>144</td>
<td>5</td>
</tr>
</tbody>
</table>

^a$B_0$: intercept; $B_1$: response to crop density; $B_2$: response to Persian darnel density

^b NS: parameter estimate not significant at $P \leq 0.05$
Figure 5. Effects of Persian darnel density on spring wheat tiller production (tiller/plant) and seed produced per tiller (seed/tiller). Data were fitted to Equation 3. Parameter estimates and regression statistics presented in Table 3.
Figure 6. Effects of Persian darnel density on canola branch production (branch/plant) and pod production (pod/branch). Data were fitted to Equation 3. Parameter estimates and regression statistics presented in Table 3.
Persian darnel density did not affect spring wheat or sunflower yield in 2000 as indicated by $i$ and $a$ parameter estimates being not different than zero (Table 1). Hence, data was subjected to analysis of covariance to test for differences in mean crop yield by seeding rate. The results indicated no difference in mean crop yield between crop seeding rates for spring wheat or sunflower in 2000 (data not shown).

Persian darnel density affected canola yield in 2000 and all crop yields in 2001 (Table 1). In 2000, canola yield did not respond with increased crop seeding rate (Table 4 and Figure 8). In 2001, spring wheat and canola yield increased as crop seeding rate was increased from 1X to 2X (Table 4 and Figures 9 and 10). In 2001, increasing sunflower seeding rate did not affect crop yield (Table 4 and Figure 11).
Crop yield increased with crop density, but increasing crop seeding rate did not always increase crop yield (Tables 1 and 4). Previous studies have shown a lack of crop yield response to increased crop seeding rate under weed infested conditions, and have attributed this lack of response to adequate crop densities at the lowest crop seeding rate to obtain the maximum yield potential (Carlson and Hill 1985; Degenhardt and Koudra 1981; Morrison et al. 1990; O'Donovan 1994). In this study, increasing crop seeding rate of spring wheat and sunflower in 2000 did not increase crop yield. The lack of crop yield response to increased crop seeding rate can be attributed to low Persian darnel interference, and to high variability in crop seedling establishment.
Table 4. Parameter estimates for data fit to non-linear model (Equation 4) showing the effects of crop seeding rate (1X, 1.5X and 2X) on crop yield. Crop yield that was not affected by Persian darnel was not fit to Equation 4. F-test indicates an increase in crop yield with increasing crop seeding rate from the 1X seed rate.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>Seed Rate</th>
<th>$i$ (SE)</th>
<th>$a$ (SE)</th>
<th>F-test Within Years $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>2000</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>-</td>
<td>-</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>1</td>
<td>0.70 (0.23)</td>
<td>94.66 (13.65)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0.88 (0.42)</td>
<td>71.71 (11.02)</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.13 (1.39)</td>
<td>52.44 (10.62)</td>
<td>***</td>
</tr>
<tr>
<td>Canola</td>
<td>2000</td>
<td>1</td>
<td>8.17 (5.68)</td>
<td>62.24 (11.53)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>6.12 (4.70)</td>
<td>61.77 (12.88)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>5.72 (2.77)</td>
<td>59.07 (9.27)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>1</td>
<td>0.83 (0.45)</td>
<td>99.99 (24.80)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>0.68 (0.34)</td>
<td>90.11 (20.98)</td>
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<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.70 (0.36)</td>
<td>74.00 (11.41)</td>
<td>*</td>
</tr>
<tr>
<td>Sunflower</td>
<td>2000</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td></td>
<td>1.5</td>
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<td>-</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>1</td>
<td>21.48 (34.23)</td>
<td>59.20 (4.09)</td>
<td>-</td>
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<td></td>
<td></td>
<td>1.5</td>
<td>30.08 (88.70)</td>
<td>51.44 (4.84)</td>
<td>NS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.01 (1.34)</td>
<td>62.61 (6.77)</td>
<td>NS</td>
</tr>
</tbody>
</table>

$^a$ F-test amongst years: F-test compares crop yield with 1X seed rate to crop yield with 1.5X and 2X seed rates. Levels of significance: * $P < 0.1$; ** $P < 0.01$; *** $P < 0.001$; NS = $P > 0.1$
Figure 8. Effects of Persian darnel density and crop seeding rate on canola yield in 2000.

Figure 9. Effects of Persian darnel density and crop seeding rate on spring wheat yield in 2001.
Figure 10. Effects of Persian darnel density and crop seeding rate on canola yield in 2001.

Figure 11. Effects of Persian darnel density and crop seeding rate on sunflower yield in 2001.
Crop Seedling Density Response to Crop Seeding Rate

Increasing the crop seeding rate increased the crop density for all crops in each year (Figure 12). Canola and spring wheat seedling establishment were higher in 2001 compared to 2000 (Figure 12), which can be attributed to higher early season precipitation in 2001. The density of sunflower was also variable due to poor and erratic crop seedling establishment prior to hand thinning (data not shown).

The mean crop density increased with crop seeding rate, however, the variability in crop seedling establishment was large (Figure 12). This variation occurred even though caution was taken to ensure even and proper seed placement during seeding. Seeding of all crops was done with a plot seeder that ensured equal amounts of counted seed were placed in the corresponding plots. Travel speed was less than 1 mph, reducing any excessive soil displacement or seeder shank flotation. Even with these precautions the variation in crop seedling establishment was large. Preliminary results indicate, crop seedling densities established using commercial seeders may have greater variation in crop seedling establishment than the variability found in this study (Carlson, personal communication; Miller, unpublished data). In order for increased crop density to be an effective weed management tool, the variability in crop seedling establishment needs to be reduced.
Figure 12. Effects of crop seeding rate on spring wheat (A) and canola (B) density in 2000 and 2001. Data were fitted to Equation 5.
Conclusions

Crop seedling establishment is critical for obtaining and maintaining crop yield potential. This and other research suggests that crop density can affect yield more than weed density, especially at low weed densities (Firbank and Watkinson 1985; Jasieniuk et al. 1999). Research has shown that higher crop densities can minimize the competitive affects of weeds by reducing weed establishment and weed impact on yield. However, crop seedling establishment in this study was highly variable. More importantly however, Persian darnel impacts on crop yield were reduced by higher crop densities, which increased critical yield components such as tillers, branches and pods. The variability in crop seedling establishment resulted in seeding rate only reducing the impact of Persian darnel on crop yield in 2 out of 4 instances. Differences in the amount of precipitation received between years might explain some of the variation in crop seedling establishment. However, seed vigor, pathogens, seeding depth, and temperature can also reduce crop seedling establishment (Hamman et al. 2002). Further research is needed to understand factors causing variability in crop seedling establishment and limit their impacts before increasing crop seeding rates can consistently reduce the impact of weed interference on crop yield. In addition, future work needs to gain understanding in the mechanism of competition, especially early in the growing season, to determine if the competitive effects of Persian darnel can be mitigated with improved resource management.

Persian darnel impacted spring wheat and canola greater than sunflower. This can be partially attributed to the delayed seeding and preplant application of glyphosate in sunflower, which reduced Persian darnel density in crop and competition for
resources early in the growth of crop and weeds. Persian darnel’s short height and shallow rooting system might cause it to be less competitive with crops with large canopies, and deeper rooting structure (Sheley and Larson 1995). Sunflower can root to deeper soil depths than Persian darnel (Figure 23, Appendix D; Jaafar et al. 1993), allowing sunflower to capture resources unavailable to Persian darnel and minimize the effect of Persian darnel on crop yield.

Persian darnel impacts on spring wheat, canola and sunflower were minimal at low densities. However crop yield loss was estimated to reach 83%, 70% and 57% for spring wheat, canola and sunflower, respectively at high Persian darnel densities. At low Persian darnel densities, herbicide treatment aimed at reducing crop yield loss might not always be economically warranted. Persian darnel interference appears to affect crop yield early in crop physiological development. If weed management is imposed, treatment should occur early in crop physiological development since late herbicide treatment intervention might not reduce Persian darnel impact on crop yield.
EFFECTS OF SPRING WHEAT, CANOLA, SUNFLOWER AND PERSIAN DARNEL (**Lolium persicum**) DENSITY ON PERSIAN DARNEL FECUNDITY

**Introduction**

Persian darnel (**Lolium persicum** Boiss. & Hoh.) can cause yield loss in spring wheat (**Triticum aestivum** L.), canola (**Brassica napus** Koch.) and sunflower (**Helianthus annuus** L.) in the northern Great Plains (NGP) (Chapter 2). The estimated maximum yield loss caused by high densities of Persian darnel was 83%, 70% and 57% for spring wheat, canola and sunflower, respectively (Chapter 2). Persian darnel can also contaminate harvested cereals, resulting in dockage fees. In a non-peer review report, low infestations of Persian darnel in spring wheat have ranged from 100 to 300 plants/m², but densities up to 2,800 plants/m² have been observed (Hunter 1984). Persian darnel emergence typically occurs from mid April through early May (Banting and Gebhardt 1979), which coincides with the NGP seeding date for cool season spring crops. The early emergence, rapid growth (Banting and Gebhardt 1979) and fibrous rooting structure (Appendix D) of Persian darnel might enable it to capture resources prior to spring seeded crops (Stone et al. 1988). The ability to obtain resources early might enable Persian darnel to reduce the competitive interference of the crop and produce seed even under moisture limiting conditions (Banting and Gebhardt 1979).

Historical dryland cropping rotations of Montana have been cereal-fallow with occasional recropping of cereal. Persian darnel populations have increased within this
cereal based cropping system, and have spread across Montana. Speculations suggest Persian darnel has spread because it has a life cycle similar to cereals, and resistance to selective graminicides used in cereal production (Weed Science Organization 2000). Few selective herbicides are available for managing Persian darnel in cereals. The only herbicides labeled for selective postemergence control in cereals are acetyl-CoA carboxylase (ACCase) inhibitors (Bussan et al. 2002).

Potential for alternative crop production has increased in the northern Great Plains over the past decade (National Agricultural Statistical Service 2001). Integrated weed management systems that incorporate the use of diverse cropping systems have been found to effectively manage annual grass weeds within dryland wheat production systems (Blackshaw 1994b; Derksen et al. 2002; Lyon and Baltensperger 1995; Young et al. 1996). Through crop diversification, crop species that vary in root and canopy architecture can be selectively grown to increase crop competitiveness and reduce weed fecundity and interference (Lanning et al. 1997; Pavlychenko and Harrington 1935). Crop diversification can also vary the timing and use of associated crop husbandry practices by growing summer, winter and nitrogen-fixing crops. A decrease in weed resource availability, and timing of herbicide application, seeding and harvest date might lower weed fecundity and reduce weed effects on crop yield (Blackshaw et al. 2001; Derksen et al. 2002; Liebman et al. 1996). Unfortunately, little work has documented the interference between weeds and different crops or crop types that might occur within a rotation. Research on crop rotations generally only document the impact of various herbicidal control measures and the impact of different crops on weed
population dynamics (Derksen et al. 2002; Doucet et al. 1999; Le’ge’re and Samson 1999).

Previous research has shown that increasing crop seeding rate can reduce weed fecundity and increase crop yield potential (Carlson and Hill 1985; Holman 2002, Chapter 2; O’Donovan 1994). Hashem et al. (1998) found the fecundity and competition of Italian ryegrass (*Lolium multiflorum* Lam.) decreased with increased winter wheat density. Canola competitiveness with wild oat (*Avena fatua* L.) decreased at crop densities less than 50 plants/m² (Lutman et al. 1994). Canola grown at densities greater than 200 plants/m² reduced Tartary buckwheat (*Fagopyrum tataricum* L.) fecundity (O’Donovan 1994). However, increasing crop seeding rate might not increase crop density, since crop seedling establishment can be highly variable (Hamman et al. 2002). Therefore, it is necessary to evaluate both crop density and crop seeding rate effects on Persian darnel fecundity.

Based on previous spring wheat research (Lanning et al. 1997; Mishra et al. 1999), we hypothesized that canola and sunflower, in rotation with spring wheat, might provide an opportunity to manage Persian darnel by exploiting differences in crop competitiveness and agronomic practices. Herbicide mode of action and selectivity, optimum seeding date, planting density and harvest date of canola and sunflower are different than spring wheat, and might be beneficially manipulated to reduce Persian darnel fecundity. Canola is potentially more competitive with Persian darnel than spring wheat because of a denser crop canopy (Kropff and Spitters 1991; Morrison et al. 1990). Sunflower is potentially more competitive with Persian darnel than either spring wheat or canola due to a later seeding date, which allows for the implementation of pre-
plant weed management (stale seedbed technique) (Buhler and Gunsolus 1996; Spandl et al. 1999). Sunflower has a deeper rooting system than spring wheat, canola or Persian darnel, which might also increase its competitiveness (Figure 23, Appendix D; Jaafar et al. 1993; Nielsen 1997; Sheley and Larson 1995).

Determining cultural management methods effective at suppressing Persian darnel should provide for more sustainable management of this weed. Crop rotation is seen as a key management technique that can be implemented into an integrated weed management plan (Derksen et al. 2002; Doucet et al. 1999; Le’ge’re and Samson 1999; Liebman et al. 1996). The objectives of this research were to quantify the effects of crop type, crop density and Persian darnel density on Persian darnel seedling establishment and fecundity.

Materials and Methods

Experimental Procedures

Field experiments were conducted in 2000 and 2001 at the Montana State University (MSU), Arthur Post Research Center near Bozeman, MT (latitude: 45° 47' N, longitude 111° 9' W). The soil type was an Amsterdam silty clay loam (fine-silty, mixed, superactive, frigid typic haplustolls, 0 to 4 % slopes) composed of 12 % sand, 53 % silt, 33 % clay, with 2 % organic matter and pH of 7.4. The 50-yr average rainfall was 42 cm/yr and the study site has been under conventional tillage for at least 25 years (Table 7, Appendix B). Spring wheat was the previous crop for each year of the study. The experimental design was a randomized complete block, with a split-plot treatment
arrangement and with three replications. The whole plot factor was crop type [spring wheat, canola, sunflower and Persian darnel monoculture (crop free)]. The subplot treatment factors were three crop seeding rates (1X, 1.5X and 2X of the recommended seeding rates) and Persian darnel seeding rates in a factorial arrangement.

Persian darnel seeding rates were determined from the previous year natural seed rain in 2000 and 2001, and supplemental Persian darnel seed was spread the fall prior to the 2001 experiment. Persian darnel natural seed rain was recorded in permanently marked plots the previous fall to determine seeding rates for the experiments. Persian darnel seed rates for the 2000 experiment ranged from 0 to 12,000 seed/m². In preparation for the 2001 trial, spring seeded Persian darnel failed to produce seed thus requiring supplemental seeding in the fall. Supplemental Persian darnel seed was spread into permanently marked plots at densities of 0, 170, 230, 280, 550, 870, 2,150, 4,150 and 6,150 seeds/m² in the fall prior to the 2001 growing season. Supplemental seed was harvested from Persian darnel growing in monoculture plots within the 2000 experiment.

The site was tilled in the spring with a disk and field cultivator prior to fertilizer application. All plots were fertilized with 336 kg/ha of 25-5-8 as N-P-K. Canola plots received an additional 112 kg/ha of ammonium sulfate (10-0-0-20). Fertilizer rates were determined from soil test results and Montana State University recommendations. Fertilizer was broadcast on the soil surface with a granular applicator and incorporated with a field cultivator prior to seeding. The targeted 1X crop seeding densities were 123, 60 and 3 plants/m² for spring wheat, canola and sunflower, respectively. The 1X crop seeding rates were 191, 190 and 4 seed/m² for spring wheat, canola and sunflower,
respectively. Viability of crop seed lots were tested before planting and seeding rates were adjusted accordingly. All crops were seeded with a double disc, cone distance-displacement plot seeder with rows spaced 25.4 cm apart. Sunflower seed can bridge in seed tubes of conical seeders, restricting the flow of seed to the seeder opener, and resulting in uneven seed placement. Therefore, sunflower was seeded at two to four times the targeted plant density and hand thinned to obtain a uniform stand of equidistantly spaced plants at the desired densities.

‘McNeil’ spring wheat and ‘Hyola 308’ canola were seeded 3.8 and 1.3 cm deep, respectively on 8 April 2000 and on 17 April 2001. Spring wheat and canola were seeded as soon as the soil was sufficiently dry to bear machinery traffic. At the time of seeding spring wheat and canola, the seeder was operated through the Persian darnel monoculture plots to simulate the same amount of soil disturbance as in the crop seeded plots but no seed was sown. Sunflower (‘Cenex 803’) has a low frost tolerance relative to spring wheat and canola and was seeded later on 16 May 2000 and on 19 May 2001. Sunflower seeding was preceded by an application of glyphosate plus ammonium sulfate at 0.42 kg ae/ha and 1.9 kg/ha to control the first cohort of weeds, a common practice in the northern Great Plains. All plots were maintained free of all weeds except Persian darnel by hand weeding throughout the growing season.

In 2000, canola seed was treated with benomyl, a fungicide, but a flea beetle (*Phyllotreta crucisera*) infestation occurred within the study. Therefore in 2001, canola seed was treated with benomyl plus imidacloprid, a systemic insecticide and fungicide, for control of flea beetle and effects of potential disease. The entire study was treated with lambda-cyhalothrin to control escaped flea beetle or sunflower beetle
(Zygograma exclamationis) populations both years. Spring wheat seed was treated with tebuconazole and imazalil, and sunflower seed was treated with metalaxyl and fludioxonil each year to reduce the potential effects of plant disease.

Data Collection

Crop and Persian darnel density and Persian darnel fecundity component data were collected from 0.25 m² circular quadrats in each subplot. Three and four quadrats per subplot were established immediately following seeding in 2000 and 2001, respectively. Subsampling was increased from 3 to 4 quadrats to improve coefficient of determination. Quadrats were located randomly with the restriction that they be at least 30 cm from the edge of the plots to reduce edge effects. Spring wheat, canola and Persian darnel seedlings were counted in each quadrat on May 20, 2000 and on May 29, 2001, when spring wheat reached the three-leaf stage (Zadock’s scale 1.3). Sunflower seedling density was determined 3 wk after seeding by hand thinning to the desired plant densities, when the majority of the sunflower plants had emerged. Sunflowers that emerged after 3 wk were removed.

Persian darnel plants were hand harvested at 3-day intervals beginning on July 10, 2000 and July 24, 2001 when the first Persian darnel plants began to mature. Plant maturity was determined by plant color and plant seed retention. Persian darnel plants were selectively harvested to minimize seed loss due to shattering. Persian darnel density (seedlings/m²), tiller production per plant (tillers/plant), seed production per plant (seeds/plant), and seed weight (g/seed) were measured. Persian darnel tiller production was determined by separating each Persian darnel plant at harvest and
counting the number of tillers produced by each plant. Persian darnel seed production was estimated in the lab by 1) removing all foreign material, 2) determining the weight of a 1,000 seed sub-sample and 3) quantifying the total weight and amount of seed produced.

**Statistical Analysis**

Data were analyzed separately for each year. Regression residuals were analyzed using a runs test for randomness, Levene’s test for constancy of variance, and a goodness of fit test for normality of error terms (Neter et al. 1996). Regression F-tests were considered significant at P ≤ 0.05.

**Persian Darnel Seedling Establishment.** The effect of crop type on Persian darnel seedling density was determined by using linear regression (Basic Statistics; StatSoft Inc. 2000) (Equation 1).

\[ N_w = \beta_0 + \beta_1 X_w + \hat{\epsilon} \]  \[1\]

\(N_w\) was Persian darnel density (seedlings/m²), \(\beta_0\) was the intercept, \(\beta_1\) was the proportion of Persian darnel seedlings established from Persian darnel seeding rate, \(X_w\) was Persian darnel seeding rate (seed/m²), and \(\hat{\epsilon}\) was an estimated error term. A nonlinear model was attempted to fit Persian darnel seedling establishment, but was unable to be fit.
After completing all regressions for Equation 1, variances, grouped by year, were tested using Levene’s test for homoscedasticity within a group (Neter et al. 1996). All regressions with homoscedastic data were then tested for differences in regression slope between crop and monoculture using an F-test. Differences in slope were determined at $P \leq 0.05$.

**Sunflower.** Persian darnel seedling density after pre-plant glyphosate application, in sunflower, was tested for correlation to Persian darnel density before application by plot to determine if Persian darnel seedling density after glyphosate application were less than prior to application. A correlation assumed that Persian darnel was capable of establishing a population density after glyphosate application to the same magnitude of density prior to glyphosate application. The correlation was tested using linear regression (Equation 2).

$$
N_w AG = \beta_0 + \beta_1 \times X_1 + \epsilon
$$

$N_w AG$ was the Persian darnel seedling density after glyphosate application (seedlings/m²), $\beta_0$ was the intercept, $\beta_1$ was the proportion of Persian darnel seedlings established after glyphosate application from Persian darnel seedling density prior to glyphosate application, $X_1$ was Persian darnel seedling density prior to glyphosate application (seedlings/m²), and $\epsilon$ was an estimated error term.

**Persian Darnel Tiller Production, Seed Production per Plant and Seed Weight**
In Monoculture. The effect of Persian darnel density on Persian darnel tiller production, seed production per plant and seed weight was tested using a nonlinear regression model (Firbank and Watkinson 1985) (Hooke-Jeeves Pattern Moves estimation procedure; StatSoft Inc. 2000) (Equation 3).

\[ w = w_m (1 + Q N_w)^{-b} \]  \[3\]

\( w \) was the mean yield (tillers produced, seed produced, or seed weight) per Persian darnel seedling, \( w_m \) was the maximum observed yield per Persian darnel seedling, \( Q \) was the area (m\(^2\)) required by Persian darnel to achieve a yield of \( w_m \), and \( b \) describes the efficiency utilization of a population. When \( b = 1 \), it is assumed that constant final yield was obtained, indicating compliance with the reciprocal yield law (Firbank and Watkinson 1985). When \( b \) was estimated to be 1, the parameter \( b \) was fixed at 1 and the model was refit to the data estimating the remaining parameters. Parameters were considered significant at \( P \leq 0.05 \).

In Crop. The effect of crop and Persian darnel density on Persian darnel tiller production, seed production per plant and seed weight was tested using a nonlinear regression model (Firbank and Watkinson 1985) (Hooke-Jeeves Pattern Moves estimation procedure; StatSoft Inc. 2000) (Equation 4).

\[ w = w_m (1 + Q (N_w + CN_c))^{-b} \]  \[4\]
was the maximum observed yield per Persian darnel seedling in monoculture, \( C \) was the competition coefficient, and \( N_c \) was crop density (seedlings/m\(^2\)). Parameter estimates were considered significant at \( P \leq 0.05 \).

**Crop Competitiveness.** Spring wheat, canola and sunflower were evaluated for their relative competitiveness to potentially reduce Persian darnel seed production per plant. Relative crop competitiveness was determined using Bonferroni confidence intervals comparing parameter estimates \( C \) and \( Q \) derived from Equation 4 by year (Neter et al. 1996). Parameter estimates were determined to be significant at \( P \leq 0.05 \).

**Crop Seeding Rate Effects on Persian Darnel Seed Production.** The effect of crop seeding rate on Persian darnel seed production (seed/m\(^2\)) was tested using linear regression (Equation 7).

\[
y = \beta_0 + \beta_1 \times X_c + \epsilon 
\]  

\( y \) was Persian darnel seed production (seed/m\(^2\)), \( \beta_0 \) was the intercept, \( \beta_1 \) was the change in Persian darnel seed production with a change in crop seeding rate, \( X_c \) is the crop seeding rate (1X, 1.5X and 2X) and \( \epsilon \) is an estimated error term. The effect of crop seeding rate on Persian darnel seed production was determined at \( P \leq 0.05 \).
Results and Discussion

Persian Darnel Seedling Establishment

Persian darnel densities were higher in 2001 compared to 2000 (Figure 13). Persian darnel densities might have been higher in 2001 due to precipitation occurring within 4-d of seedbed preparation and crop seeding (Table 7 and Figure 21, Appendix B), warmer soil temperatures early in the growing season, potentially higher seed vigor, and potentially fewer pathogens (Banting and Gebhardt 1979; Hamman et al. 2002). In 2000, precipitation was not received until after initial flushes of spring wheat, canola and Persian darnel had already emerged.

Table 5. Effect of crop type on Persian darnel seedling establishment. Data were fit to Equation 1. F-test indicates difference in Persian darnel seedling establishment (slope) between Persian darnel monoculture and crop by year.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>B₀ (SE)</th>
<th>F-testᵃ</th>
<th>B₁ (SE)</th>
<th>F-test</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monoculture</td>
<td>2000</td>
<td>181.81 (24.31)</td>
<td></td>
<td>0.073 (0.017)</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>196.67 (9.06)</td>
<td></td>
<td>0.135 (0.0034)</td>
<td></td>
<td>0.55</td>
</tr>
<tr>
<td>Spring wheat</td>
<td>2000</td>
<td>85.77 (41.74)</td>
<td>***</td>
<td>0.036 (0.019)</td>
<td>**</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>43.68 (13.54)</td>
<td>*</td>
<td>0.205 (0.0055)</td>
<td>***</td>
<td>0.76</td>
</tr>
<tr>
<td>Canola</td>
<td>2000</td>
<td>31.29 (42.64)NS</td>
<td>***</td>
<td>0.008 (0.018)</td>
<td>***</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>115.94 (13.54)</td>
<td>NS</td>
<td>0.101 (0.0055)</td>
<td>***</td>
<td>0.59</td>
</tr>
<tr>
<td>Sunflower</td>
<td>2000</td>
<td>4.14 (40.53)NS</td>
<td>***</td>
<td>0.001 (0.029)NS</td>
<td>***</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>31.25 (13.54)</td>
<td>*</td>
<td>0.042 (0.0055)</td>
<td>***</td>
<td>0.77</td>
</tr>
</tbody>
</table>

ᵃ F-test by year: * P < 0.05; ** P < 0.01; *** P < 0.001; NS, not significant

Persian darnel seedling establishment was highest in monoculture and was reduced in spring wheat, canola and sunflower (Table 5 and Figure 13). Reduced Persian darnel seedling establishment in sunflower can be attributed to a delay in crop
seeding date and a pre-plant application of glyphosate which controlled early emerging cohorts. Persian darnel seedling establishment was greatly reduced in canola compared to spring wheat both years even though canola and spring wheat were seeded on the same date. Why Persian darnel seedling establishment was lower in canola compared to spring wheat was not clear.

Previous studies have shown that different crop residues can affect weed seedling establishment and that certain Brassicaceae residues are potentially allelopathic (Chew 1998; Vaughn and Boydston 1997). However, in this study all crops were grown following spring wheat. Therefore, differences in Persian darnel seedling establishment were not due to differences in crop residue. The ability of canola seedlings to affect Persian darnel or other germinating weed seedlings does not appear to be understood or even reported previously. Inderjit and Streibig (2001) did report that perennial ryegrass (Lolium perenne L.) root growth was reduced with increased wheat seed density in a lab environment. They concluded that ryegrass root growth was reduced by either root exudates of wheat, or from competition amongst crop and ryegrass roots for space. Research has shown that crop shading can reduce seedling establishment (Kasperbauer and Karlen 1994), but Persian darnel seedling establishment was affected early in the growing season prior to substantial canopy development. Thus, crop shading was minimal and unlikely affected Persian darnel seedling establishment. Although the mechanism affecting Persian darnel seedling establishment is not known, differences in Persian darnel seedling establishment occurred by crop type. The effect on seedling establishment could reduce Persian darnel interference with crops and fecundity.
Sunflower. Persian darnel seedling densities in sunflower were greatly diminished after the glyphosate application than prior to the glyphosate application in both years (Figure 14). In 2000, no correlation occurred between Persian darnel seedling densities before and after glyphosate application. Mean Persian darnel seedling density after glyphosate application was 5.5 seedlings/m² in 2000. In 2001, Persian darnel density after glyphosate was 8% of the density prior to glyphosate application (Figure 14).

Research results in 2000 contradict research of Deileman et al. (1999), which conclude that a positive linear relationship occurred between the first cohort of emerged velvetleaf (Abutilon theophrasti Medic.) and common sunflower (Helianthus annuus L.) seedlings and the density of weed seedlings after herbicide treatment. Deilemen et al. (1999) also concluded that as management intensity increased, the remaining weed population decreased. Persian darnel densities after glyphosate application might have been less in 2000 compared to 2001 because glyphosate application and sunflower seeding occurred later in 2000. The earlier glyphosate application in 2001 likely controlled a smaller percentage of the emerging weed seedbank compared to 2000. Also, substantial precipitation did not occur until June of 2001, which might have caused later Persian darnel seedling emergence. The research conclusions of Deilemen et al. (1999) might not be consistent with early emerging weed species and late seeded crops.
Figure 13. Relationships between Persian darnel seed rain in 1999 (A) and 2000 (B) on Persian darnel seedling density in 2000 (A) and 2001 (B), respectively for spring wheat, canola, sunflower and monoculture. Data were fitted to Equation 1. Parameter estimates and regression statistics are shown in Table 5.
Figure 14. The effect of glyphosate on Persian darnel re-establishment density in 2000 (A) and 2001 (B). Data were fitted to Equation 2.

\[ Y = 53 + 0.08X_1 \]
\[ R^2 = 0.79 \]
In Monoculture. Increasing Persian darnel density in monoculture reduced Persian darnel tiller production (tiller/seedling) and seed production per plant (seed/seedling) in each year (Figure 15). Increasing Persian darnel density did not affect seed weight (g/seed) in either year (data not shown). These results indicate Persian darnel intraspecific interference likely occurred early in plant development, impacting tiller production, which in turn reduced seed production on a per plant basis. The model used in the analysis had not been previously reported to quantify an affect on tiller production or seed weight, but the model fit the data explaining 70% and 84% of the variability in Persian darnel tiller production in 2000 and 2001, respectively. The model accounted for 65% and 63% of the variability in seed production per plant in 2000 and 2001, respectively. Seed production per plant in monoculture ranged from 63 to 800 seed in 2000 and 14 to 803 seed in 2001. This research combined with information on seedbank dynamics of Persian darnel can be used to predict the impact of Persian darnel on future densities and potential impacts on crop yield (Cousens 1985a; Martin et al. 1987).

In Crop. The level of intra and interspecific interference of crop and Persian darnel density can be partially explained by their influence on the components of Persian darnel fecundity. This analysis evaluated the area (m²) required for an individual Persian darnel plant to obtain maximum yield production per plant (parameter Q), the competitive indices of crop and weed on seed production per plant
(parameter $C$), and the ability of Persian darnel to compensate for the effects of increasing plant density or intraspecific interference (parameter $b$) (Firbank and Watkinson 1985).

An effect of crop density on Persian darnel tiller production was not detected for any crop in either year (data not shown). In both years the effect of interspecific interference was as great or greater than the effect of intraspecific interference on Persian darnel seed production per plant; as indicated by the competition coefficient (parameter $C$) being equal to or greater than 1 (Firbank and Watkinson 1985) (Table 6). In 2000, canola density affected Persian darnel seed production per plant as indicated by parameter $C$ (Table 6 and Figure 16), but spring wheat and sunflower density did not affect seed production per plant (Table 6). The results from canola, in 2000, suggest that each crop seedling had an effect 0.99 of 1 Persian darnel seedling on per plant seed production. In 2001, spring wheat and canola density affected seed production per plant (Table 6 and Figures 17 and 18), but sunflower density did not affect seed production per plant (Table 6). In 2001, the results suggest that spring wheat had an effect 1.16 of 1 Persian darnel plant, and that canola had an effect 2.70 of 1 Persian darnel plant on seed production per plant. In 2001, canola density also affected Persian darnel seed weight [$Q = 0.005 (0.005)] [C = 2.33 (0.999)]$ (Figure 19). These results suggest that canola density might of had the greatest effect on Persian darnel seed production per plant, and that sunflower density had least effect on Persian darnel seed production per plant.

Persian darnel tiller production might have not been affected by crop density because Persian darnel has been indicated to emerge and grow rapidly in the spring.
(Banting and Gebhardt 1979; Bussan and Dietz-Holmes 2000), and this might have minimized the affect of crop competition on Persian darnel tiller production. Previous research has shown early emerging weed cohorts to be affected less by crop competition than later emerging cohorts (Mickelson and Harvey 1999; Peters and Wilson 1983; Smith and Jordan 1993).

Previously, it was reported that Persian darnel did not impact spring wheat yield in 2000 (Holman 2002, Chapter 2). In addition, spring wheat did not impact Persian darnel seed production in 2000 (Table 6). The lack of identifying interference between spring wheat and Persian darnel in 2000 might be attributed to variability in the data, or due to a lack of interference potentially caused by low Persian darnel densities in spring wheat in 2000 and more early growing season precipitation in 2000 compared to 2001 (Table 7 and Figure 21, Appendix B). The lack of effect of sunflower or Persian darnel density on Persian darnel seed production might also be due to variability in the data, or because of low weed densities after the glyphosate application reducing intraspecific interference and slow aboveground growth of sunflower early in the growing season reducing interspecific interference. Other research on the competitive interaction of sunflower with weeds has also confirmed that sunflower is a poor competitor early in the growing season due to its slow initial aboveground growth (Durgan et al. 1990; Johnson 1971).

The results of this research are similar to the findings of Hashem et al. (1998), who studied the competitive interactions of winter wheat and Italian ryegrass (Lolium multiflorum Lam.). Hashem et al. (1998) concluded that winter wheat affected Italian ryegrass early in plant development by reducing plant size and seed production. In this
study, we did not measure Persian darnel vegetative components. However, the results of this study do indicate that crop and Persian darnel interference occurred early in the growing season and that crop interference reduced Persian darnel seed production with little impact on Persian darnel seed weight.

**Crop Competitiveness.** The influence of crop density, parameter $C$, on Persian darnel seed production per plant was not different among crop types in either year (Table 6). Differences in parameter estimates were not found due to large parameter standard errors. In 2000, the area ($m^2$) required for Persian darnel to obtain maximum seed production potential, $Q$, was not different between monoculture, spring wheat and canola. $Q$ was greatest in sunflower, and was not different from canola. In 2000, it required 0.01 $m^2$ in monoculture, 0.04 $m^2$ in spring wheat, 0.41 $m^2$ in canola, and 0.79 $m^2$ in sunflower to obtain $Q$ (Table 6). In 2001, $Q$ was not different between monoculture, canola and sunflower (Table 6). $Q$ was greater in spring wheat compared to monoculture, but was not different from canola or sunflower. In 2001, it required 0.01 $m^2$ in monoculture, 0.07 $m^2$ in spring wheat, 0.15 $m^2$ in canola, and 1.00 $m^2$ in sunflower to obtain $Q$. The area required for Persian darnel to maximize seed production per plant, parameter $Q$, was consistently lower in monoculture across years, indicating that crop interference was increasing the area required for Persian darnel to obtain its maximum seed production. The area required for Persian darnel to obtain maximum seed production per plant was consistently greatest in sunflower; this might
Figure 15. The effect of Persian darnel density on Persian darnel tiller production (tiller/seedling) and seed production (seed/seedling) in monoculture. Data were fitted Equation 3.
Figure 16. The effect of canola and Persian darnel density on Persian darnel seed production (seed/seedling) in 2000. Data were fitted to Equation 4.

Figure 17. The effect of spring wheat and Persian darnel density on Persian darnel seed production (seed/seedling) in 2001. Data were fitted to Equation 4.
Figure 18. The effect of canola and Persian darnel density on Persian darnel seed production (seed/seedling) in 2001. Data were fitted to Equation 4.

Figure 19. The effect of canola and Persian darnel density on Persian darnel seed weight (g/seed) in 2001. Data were fitted to Equation 4.
Table 6. Persian darnel seed produced per plant in response to crop and Persian darnel density. Parameter estimates for Persian darnel seed production in monoculture derived from nonlinear yield model (Equation 3). Parameter estimates for Persian darnel seed production in crop derived from nonlinear yield model (Equation 4). Parameter estimates \( Q \) and \( C \) were compared amongst crop separately by year. Differences in parameter estimates was determined at \( P < 0.05 \)

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>( Q^a )</th>
<th>( Q^b )</th>
<th>( C^a )</th>
<th>( C^b )</th>
<th>( b )</th>
<th>( R^2 )</th>
<th>n</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Monoculture</td>
<td>0.01 (0.001)</td>
<td>a</td>
<td>-</td>
<td>a</td>
<td>1</td>
<td>0.65</td>
<td>80</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>0.04 (0.02)</td>
<td>a</td>
<td>4.15 (2.43) NS</td>
<td>a</td>
<td>1</td>
<td>0.10</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>0.41 (0.42) NS</td>
<td>a,b</td>
<td>0.99 (0.49)</td>
<td>a</td>
<td>0.67 (0.17)</td>
<td>0.22</td>
<td>80</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>0.79 (0.29)</td>
<td>b</td>
<td>0.99 (0.83) NS</td>
<td>a</td>
<td>1</td>
<td>0.10</td>
<td>80</td>
<td>4</td>
</tr>
<tr>
<td>2001</td>
<td>Monoculture</td>
<td>0.01 (0.001)</td>
<td>x</td>
<td>-</td>
<td>x</td>
<td>0.77 (0.04)</td>
<td>0.84</td>
<td>144</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>0.07 (0.02)</td>
<td>y</td>
<td>1.16 (0.54)</td>
<td>x</td>
<td>1</td>
<td>0.37</td>
<td>144</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>0.15 (0.17) NS</td>
<td>x,y</td>
<td>2.70 (1.13)</td>
<td>x</td>
<td>0.44 (0.09)</td>
<td>0.20</td>
<td>144</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>1.00 (1.57) NS</td>
<td>x,y</td>
<td>111 (112) NS</td>
<td>x</td>
<td>0.34 (0.09)</td>
<td>0.07</td>
<td>144</td>
<td>4</td>
</tr>
</tbody>
</table>

* Parameter estimates fit to yield per plant model (Equation 2): \( Q \), represents the area required by a plant to achieve an average yield of an isolated plant; and \( C \), is the competition coefficient.

* Parameter estimates were compared individually by year. The letter set (a-c) for 2000 and (x-z) 2001.

be attributed to Persian darnel growing during a non-optimal period of the growing season and fewer resources, which might have reduced Persian darnel seed production potential.

The ability of Persian darnel to obtain its maximum seed production potential/m² was indicated by parameter \( b \). When \( b = 1 \), it is assumed that plant density was high enough to obtain constant final yield (constant final yield law). In 2000, constant final yield was not obtained in canola. In 2001, constant final yield was not obtained in monoculture, canola, or sunflower. These results suggest that crop type affected Persian darnel seedling density and thus affected total seed production/m².

These results are supported by the results of Persian darnel seedling establishment in crop (Table 1). Persian darnel seedling establishment was least in canola and sunflower, and which reduced Persian darnel's ability to obtain maximum seed
production. In monoculture, in 2001, constant final yield might have not been obtained because densities were too low.

**Crop Seeding Rate Effects on Persian Darnel Seed Production**

In 2000 and 2001, increasing crop seeding rate did not affect Persian darnel seed production (seed/m²) (data not shown). Previously, it was determined that only canola in 2000 and canola and spring wheat in 2001 decreased the number of seed produced per Persian darnel seedling (Table 6). Therefore, we would expect an increase in crop seeding rate of only those crops to affect Persian darnel seed production (seed/m²). Increasing crop seeding rate tended to increase crop density, however, crop seedling establishment was highly variable (Holman 2002, Chapter 2). The variability in crop seedling establishment might help to explain why increased crop seeding rate was ineffective at reducing Persian darnel seed production.

**Conclusions**

Persian darnel can produce up to 800 seed/plant at low monoculture densities. However, increasing spring wheat density was effective in 1 out of 2 years, and increasing canola density was effective each year at reducing Persian darnel seed production per plant. Increasing crop seeding rate did not significantly reduce Persian darnel seed production either year. Further research is needed to determine if the variability in crop seedling establishment and higher cost associated with increased crop seeding rate are an economically justifiable weed management option for early emerging weed species.
Crop type was effective at reducing Persian darnel seedling establishment, and hence Persian darnel seed production/m². Sunflower reduced Persian darnel seedling establishment 99% and 70%, while canola reduced Persian darnel seedling establishment 90% and 25% compared to monoculture in 2000 and 2001, respectively. Delaying seeding and applying a preplant application of glyphosate might have caused a large reduction in Persian darnel seedling establishment, and hence Persian darnel fecundity in sunflower. However, delaying crop seeding in moisture limited conditions has the potential to reduce crop yield and economic return, and therefore might not be the best weed management control option (Khan et al. 1996).

This research suggests that by growing competitive crop species and establishing competitive crop densities one can decrease Persian darnel seed production in the absence of herbicides. Through rotating to alternative crops, herbicide selectivity and modes of herbicide action management tactics are diversified. Combining increased herbicide options, higher crop densities and competitive crop species should result in improved and more sustainable Persian darnel management.
APPENDIX A

PERSIAN DARNEL DISTRIBUTION IN MONTANA
Figure 20. Montana counties infested with Persian darnel as of 2000. Counties shaded represent level of infestation (white = no reported infestation, gray = moderate infestation, black = heavy infestation). (Wilderness Invaders Project 2002)
APPENDIX B

EXPERIMENTAL SITE INFORMATION
Table 7. Precipitation levels of 2000, 2001, and 50 year average

<table>
<thead>
<tr>
<th>Month</th>
<th>Precipitation Amount (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 yr Average</td>
</tr>
<tr>
<td>January</td>
<td>1.42</td>
</tr>
<tr>
<td>February</td>
<td>1.30</td>
</tr>
<tr>
<td>March</td>
<td>2.90</td>
</tr>
<tr>
<td>April</td>
<td>3.86</td>
</tr>
<tr>
<td>May</td>
<td>7.01</td>
</tr>
<tr>
<td>June</td>
<td>6.73</td>
</tr>
<tr>
<td>July</td>
<td>3.63</td>
</tr>
<tr>
<td>August</td>
<td>3.43</td>
</tr>
<tr>
<td>September</td>
<td>4.39</td>
</tr>
<tr>
<td>October</td>
<td>3.66</td>
</tr>
<tr>
<td>November</td>
<td>2.21</td>
</tr>
<tr>
<td>December</td>
<td>1.52</td>
</tr>
<tr>
<td>Year total</td>
<td>42.06</td>
</tr>
</tbody>
</table>

Table 8. MSU soil analytical results for Arthur Post Research Center

<table>
<thead>
<tr>
<th>Soil Characteristic</th>
<th>2000</th>
<th>2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (mg/kg)</td>
<td>440</td>
<td>325</td>
</tr>
<tr>
<td>Olsen Phos (mg/kg)</td>
<td>14.2</td>
<td>12.75</td>
</tr>
<tr>
<td>CEC (meq/100g)</td>
<td>22.53</td>
<td>22.49</td>
</tr>
<tr>
<td>EC mmhos/cm (1 to 2)</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Bouyoucos Sand %</td>
<td>10.67</td>
<td>17</td>
</tr>
<tr>
<td>Mechanical Anal. Silt %</td>
<td>54.33</td>
<td>52</td>
</tr>
<tr>
<td>Bouyoucos M.A. Clay %</td>
<td>35</td>
<td>31</td>
</tr>
<tr>
<td>NO3-N (mg/kg)</td>
<td>5.3</td>
<td>8.05</td>
</tr>
<tr>
<td>NH4-N</td>
<td>2.43</td>
<td>3.7</td>
</tr>
<tr>
<td>SO4-S (mg/kg)</td>
<td>5.2</td>
<td>7.3</td>
</tr>
<tr>
<td>Organic Matter %</td>
<td>1.94</td>
<td>2.23</td>
</tr>
<tr>
<td>pH (1 to 2)</td>
<td>7.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Water (1/3 Bar)</td>
<td>0.32</td>
<td>0.29</td>
</tr>
<tr>
<td>Water (15 Bar)</td>
<td>0.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Texture</td>
<td>Silty Clay Loam</td>
<td>Silty Clay Loam</td>
</tr>
</tbody>
</table>
Figure 21. Weekly growing season precipitation in 2000 and 2001. Weekly precipitation shown from first week of March to second week in September. Spring wheat and canola were seeded week 6 (8 April 2000) and week 7 (17 April 2001). Sunflower was seeded week 11 (16 May 2000) and (19 May 2001). Spring wheat was harvested week 16 (30 July 2000) and week 23 (20 August 2001). Canola was harvested week 16 (26 July 2000) and week 18 (12 August 2001). Sunflower was harvested week 26 (15 September 2000) and week 25 (8 September 2001).
APPENDIX C

CROP QUALITY ANALYSIS
The effect of crop and Persian darnel density on crop quality attributes for spring wheat, canola and sunflower were evaluated in this study. The crop quality attributes measured included test weight, protein or oil content, and weed dockage. Spring wheat test weight and protein content were not affected by Persian darnel, but the protein content of spring wheat decreased with increasing crop density in 2000 and 2001 (Table 9). Persian darnel increased the test weight of canola in 2000 and 2001 (Table 10). Canola oil content decreased with increasing Persian darnel and crop density in 2000 (Table 10). Sunflower test weight increased with increasing crop density in 2000 and 2001, but was not affected by Persian darnel (Table 11). Persian darnel increased the oil content of sunflower in 2001 (Table 11). Persian darnel and crop density effect on crop quality varied between study years; which might have been attributed to differences in environmental conditions. Early growing season precipitation was greater in 2000 than 2001, while late growing season precipitation was greater in 2001 than 2000 (Table 7 and Figure 21, Appendix B). Canola oil content was only affected by crop and Persian darnel density in 2000. This might have been attributed to less precipitation late in the growing season. However, minimal variation in crop quality response could be explained by either crop or Persian darnel density. Thus indicating other independent factors are affecting crop quality. One factor might be the environmental condition during the growing season, including temperature and precipitation levels.

Persian darnel caused weed dockage in harvested spring wheat and canola, but not in sunflower (Table 12). Persian darnel did affect weed dockage in sunflower due
to a lower canopy height than either the sunflower crop canopy or cutting height of the combine. Increasing the crop density of spring wheat reduced weed dockage, but increasing the crop density of canola was only negatively correlated with weed dockage. Crop and weed density effects on crop quality and on the previously modeled crop yield will be used to predict adjusted gross return in a future manuscript.
Table 9. Spring wheat quality attribute (test weight and protein) response to crop and weed density. Years tested for homoscedasticity using Brown-Forsythe (B-F) test. Years with homogenous variance tested for differences in slope with F-test ($P < 0.10$). For non-significant F-tests, parameter estimates compared with dummy variables ($P < 0.10$). Years with non-homogenous variances were regressed using weighted least squares regression. Parameter estimates: intercept ($B_0$), response with increase in crop density ($B_1$), and response with increase in Persian darnel (LOLPS) density ($B_2$) fitted using multiple linear regression.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>B-F</th>
<th>Df num</th>
<th>Df den</th>
<th>Ratio</th>
<th>Sig</th>
<th>Year</th>
<th>Wt. Reg.</th>
<th>F-test</th>
<th>Regression</th>
<th>Intercept</th>
<th>Crop density</th>
<th>LOLPS density</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test weight</td>
<td>N</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>*</td>
<td>2000</td>
<td>61.87 (0.74) ***</td>
<td>0.0014 (0.0034) NS</td>
<td>0.0025 (0.0015) NS</td>
<td>0.079</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td>Y</td>
<td>3</td>
<td>157</td>
<td>2</td>
<td>*</td>
<td>C</td>
<td>13.81 (0.27) ***</td>
<td>-0.0032 (0.0012) ***</td>
<td>-0.0001 (0.0003) NS</td>
<td>0.043</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F-test significant at: * $P < 0.1$; ** $P < 0.01$; *** $P < 0.001$; NS, not significant

C = Data combined across years
Table 10. Canola quality attribute (test weight and oil content) response to crop and weed density. Years tested for homoscedasticity using Brown-Forsythe (B-F) test. Years with homogenous variance tested for differences in slope with F-test (P < 0.10). For non-significant F-tests, parameter estimates compared with dummy variables (P < 0.10). Parameter estimates: intercept (B0), response with increase in crop density (B1), and response with increase in Persian darnel (LOLPS) density (B2) fitted using multiple linear regression.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>F-test</th>
<th>Intercept</th>
<th>Crop density</th>
<th>LOLPS density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-F</td>
<td>Df num</td>
<td>Df den</td>
<td>Ratio</td>
</tr>
<tr>
<td>Test weight</td>
<td>Y</td>
<td>3</td>
<td>132</td>
<td>6</td>
</tr>
<tr>
<td>Oil content</td>
<td>Y</td>
<td>3</td>
<td>133</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* F-test significant at: * P < 0.1; ** P < 0.01; *** P < 0.001; NS, not significant

b C = Data combined across years

c F-test indicates difference in parameter estimates by year
Table 11. Sunflower quality attribute (test weight and oil content) response to crop and weed density. Years tested for homoscedasticity using Brown-Forsythe (B-F) test. Years with homogenous variance tested for differences in slope with F-test (P < 0.10). For non-significant F-tests, parameter estimates compared with dummy variables (P < 0.10). Parameter estimates: intercept (B0), response with increase in crop density (B1), and response with increase in Persian darnel (LOLPS) density (B2) fitted using multiple linear regression.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>F-test</th>
<th>Intercept</th>
<th>Crop density</th>
<th>LOLPS density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B-F</td>
<td>Df num</td>
<td>Df den</td>
<td>Ratio</td>
</tr>
<tr>
<td>Test weight</td>
<td>Y</td>
<td>3</td>
<td>211</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil content</td>
<td>Y</td>
<td>3</td>
<td>211</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* F-test significant at: * P < 0.1; ** P < 0.01; *** P < 0.001; NS, not significant

b F-test indicates difference in parameter estimates by year
Table 12. Weed dockage response to crop and weed density. Log transformation on dependent variables with non-homogenous variances. Parameter estimates: intercept ($B_0$), response of crop density ($B_1$), response of Persian darnel (LOLPS) ($B_2$) and response of crop and Persian darnel interaction fitted using multiple linear regression.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Log Trans.</th>
<th>$B_0$ (SE)</th>
<th>Sig$^a$</th>
<th>$B_1$ (SE)</th>
<th>Sig</th>
<th>$B_2$ (SE)</th>
<th>Sig</th>
<th>$B_3$ (SE)</th>
<th>Sig</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring wheat</td>
<td>N</td>
<td>0.178 (0.187)</td>
<td>NS</td>
<td>-</td>
<td>NS</td>
<td>0.0266 (0.0018)</td>
<td>***</td>
<td>-0.00007 (0.00001)</td>
<td>***</td>
<td>0.954</td>
</tr>
<tr>
<td>Canola</td>
<td>Y</td>
<td>3.155 (0.324)</td>
<td>***</td>
<td>-0.0007 (0.015)</td>
<td>NS</td>
<td>0.0015 (0.0003)</td>
<td>***</td>
<td>-</td>
<td>NS</td>
<td>0.691</td>
</tr>
<tr>
<td>Sunflower</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$ F-test significant at: * P < 0.1; ** P < 0.01; *** P < 0.001; NS, not significant
APPENDIX D

CROP AND PERSIAN DARNEL ROOTING DEPTH
Soil moisture readings for spring wheat, canola, sunflower and Persian darnel were taken at the end of the growing season in 2001 to estimate rooting depth. This corresponds with previous studies, which have estimated rooting depth by measuring soil moisture content at the end of the growing season or after soil moisture depletion (Dardanelli et al. 1997). Measuring soil moisture content when soil moisture is depleted minimizes the stochasticity in moisture readings caused by rainfall and soil moisture reserves. Minimal precipitation occurred at the end of the growing season prior to measuring soil moisture, but an increase in soil moisture below the upper 20 cm soil layer did not occur.

Previously, soil samples from the same study site were measured with a neutron probe and then sequentially submitted for lab analysis of moisture content (Wraith, unpublished data). Soil moisture content was then linearly regressed with corresponding neutron probe readings to obtain a neutron probe reading to volumetric soil moisture conversion factor. The linear correlation resulted in a correlation estimate with a coefficient of determination of 0.92. Presenting data using volumetric soil moisture content allows data to be presented in a standard and applicable format.

A neutron moisture probe was used to measure soil moisture content at 20 cm soil depth increments for each crop monoculture and Persian darnel monoculture. It was assumed that soil type, water content, and precipitation were uniform across the study site. Volumetric soil moisture content was converted to soil matric potential using Van Genuchten soil moisture retention model, as reported by Wraith and Or (1998) (Equation 1):
\[ 2(\Theta) = 2_r + (2_s - 2_r) \ast [1 + (\forall \ast \Theta \ast)^n]^{-m} \] 

where \( \Theta \) is the matric potential, \( 2_r \) and \( 2_s \) are the residual and saturated water contents, respectively, and \( \forall, n \) and \( m \) are fitted parameters dependant on the shape of the \( 2(\Theta) \) curve. The soil moisture retention model and corresponding parameter estimates were fit using nonlinear regression (Figure 22). All parameter estimates were significant \( (P = 0.05) \), with the exception of \( \forall \) \( (P = 0.19) \). At -0.33 to -15 bar soil matric potential, the soil moisture content is approximately 0.30 cm\(^3\)/cm\(^3\) and 0.12 cm\(^3\)/cm\(^3\), respectfully (data not shown). The difference between -0.33 to -15 bar soil matric potential is the soil moisture holding capacity. The soil moisture holding capacity for the study site is 0.18 cm\(^3\) of water/cm\(^3\) of soil.

Soil matric potential was regressed against soil depth for each crop and Persian darnel separately. A logarithmic function was unable to fit the data set due to the lack of observations and stochastic response; Therefore, a least squares regression was fit the data set. It was assumed from other research that soil moisture was ineffectively extracted, or plant rooting ceased, at a soil depth of a matric potential greater than -1 bar \( (\text{Gregory 1998}) \). The regression indicated that Persian darnel and canola rooted to 60 cm, spring wheat rooted to 100 cm, and sunflower rooted below 140 cm \( (\text{Figure 23}) \). The deeper rooting depth of sunflower allows it to capture soil resources in an area unattainable by Persian darnel. The estimated rooting depth of spring wheat and canola in this study are less than previously reported \( (\text{Mishra et al. 1999; Nielsen 1997}) \). The
lower estimated rooting depth of this study might be attributed to differences in soil type, moisture content, or a conservative estimate of rooting depth.

Variation in the measured soil moisture content was least for Persian darnel. A low variation in soil moisture content indicates a fibrous rooting system with the ability to effectively utilize all available soil moisture to a specific soil matric potential (Figure 23). These results are similar to previously reported research conducted on another Lolium sp., Italian ryegrass (Stone et al. 1998). The soil matric potential of sunflower plots showed higher soil matric potential than spring wheat, canola or Persian darnel. This indicates that sunflower extracts soil moisture at higher soil matric potentials than spring wheat, canola or Persian darnel.

Soil samples from the upper 30 cm of the soil profile were collected in the spring of 2001 following Persian darnel monoculture and spring wheat monoculture grown regions in 2000, and submitted to MSU soil lab for analysis. Soil test results showed similar nutrient levels remaining in the two soil regions for nitrogen, phosphorus, potassium, and sulfur. These results suggest that Persian darnel uses approximately the same amount and level of nutrients as spring wheat.
Figure 22. Soil moisture retention curve of Arthur Post Agronomy Farm. Data were fitted to Van Genuchten equation (Equation 1).
Figure 23. Soil matric potential (at the end of growing season) response to increasing soil depth in spring wheat, canola, sunflower and Persian darnel monoculture plots. It was assumed that a soil matric potential greater than -1 bar was not affected by root water extraction.
APPENDIX E

ADDITIONAL INTERFERENCE DATA ANALYSIS
Crop Yield Response

Effect of Crop and Persian Darnel Density. Increasing crop density increased crop yield for all crops in 2000 and 2001 (Table 1). Other studies have repeatedly shown increases in crop yield due to increasing crop density in the presence of weed interference (O’Donovan 1994; Weiner et al. 2001). Persian darnel did not affect spring wheat or sunflower yield in 2000 (Table 13). These results indicate why the parameter estimates, $i$ and $a$ (Table 1) (Holman 2002, Chapter 2) for 2000 were not fit for spring wheat and resulted in a poor fit for sunflower yield response. The poor parameter estimation of the model was likely due to the fact that Persian darnel did not affect crop yield. The lack of Persian darnel impact on crop yield in 2000 can be attributed to lower weed densities and greater growing season precipitation in 2000 compared to 2001.

Table 13. Crop yield response to Persian darnel and crop seedling density fit using multiple linear regression.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year</th>
<th>Persian darnel</th>
<th>Crop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$B_1$ (SE)</td>
<td>$B_2$ (SE)</td>
</tr>
<tr>
<td>Spring wheat</td>
<td>2000</td>
<td>-0.009 (0.011)</td>
<td>0.106 (0.026)</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>-0.025 (0.003)</td>
<td>0.051 (0.018)</td>
</tr>
<tr>
<td>Canola</td>
<td>2000</td>
<td>-0.145 (0.032)</td>
<td>0.128 (0.035)</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>-0.041 (0.005)</td>
<td>0.094 (0.021)</td>
</tr>
<tr>
<td>Sunflower</td>
<td>2000</td>
<td>-0.012 (0.005)</td>
<td>6.129 (0.935)</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>-0.025 (0.003)</td>
<td>0.051 (0.018)</td>
</tr>
</tbody>
</table>
Persian Darnel Fecundity

Non-linear regression was used to determine crop and Persian darnel density effects on Persian darnel fecundity (seed production/m²). Each crop and Persian darnel monoculture was fitted separately by year to a combined modified semi-hyperbolic model. When spring wheat and canola were fit to the model, Persian darnel monoculture data for that year was included into the data set. Persian darnel monoculture data was not combined with the sunflower data set because the Persian darnel cohort growing in sunflower had emerged a month after the Persian darnel cohort growing in monoculture. The second component of the model was modified from its original format (Jasieniuk et al. 1999) (Equation 1). The second component of the model was replaced with a linear component because a hyperbolic response could not be fit to crop density (Equation 2):

\[
FEC = \left[ \frac{j \cdot N_w}{1 + j \cdot N_w / k} \right] \cdot [1 - i \cdot N_c]
\]  

where \(FEC\) was the predicted Persian darnel fecundity (seeds/m²), \(N_w\) was Persian darnel density (seedlings/m²), \(N_c\) was crop density (seedlings/m²) and \(j, k\) and \(i\) are parameters estimated with nonlinear regression. Parameter \(j\) represents weed seed production per plant as weed density approaches zero. Parameter \(k\) represents maximum seed production (seeds/m²) as Persian darnel density approaches infinity.
Parameter $i$ represents the change in Persian darnel seed production/m² with an increase in crop density. Parameter estimates were considered significant at $P \leq 0.05$.

**Persian darnel Fecundity**

Increasing Persian darnel density increased Persian darnel fecundity in each year (Table 14 and Figures 24 and 25). Increasing crop density of all crops reduced Persian darnel fecundity in each year, as shown by parameter $i$ (Table 14 and Figures 24 and 25). Persian darnel fecundity in monoculture was higher in 2000 than 2001 (Table 14). Higher Persian darnel fecundity in 2000 might be due, in part, to more early growing season precipitation in 2000 than 2001 (Table 7 and Figure 21, Appendix B). Not all parameters estimated by the model were significant according to F-tests ($P \leq 0.05$). Parameter $j$, fecundity at low Persian darnel density in monoculture, was not significant for Persian darnel monoculture data in 2000 (Table 14). Parameter $k$, fecundity as Persian darnel density approached infinity was not significant for sunflower in 2000 (Table 14). Parameter estimates were likely not estimated due to an insufficient number of observations, variability in Persian darnel fecundity response and an insufficient range of crop or weed densities observations.

I acknowledge that previous research has suggested both the effect of interspecific interference on yield and constant final yield to be fit best with a nonlinear function (Cousens 1985a, 1985b; Jasieniuk et al. 1999; Jasieniuk et al. 2001; Martin et al. 1987). However, due to an insufficient range of crop densities and variability in the effect of crop density on Persian darnel fecundity, a nonlinear function of crop density effect on Persian darnel fecundity was unable to be fit. Other research has also been
unable to fit a nonlinear response of yield, and have instead fit a linear response of yield to interference (Harrison et al. 2001; Rejmanek et al. 1989; Webster et al. 2000). However, problems arise in interpretation of the biological processes when yield response is fit linearly (Cousens et al. 1987). The model used in this study accounted for Persian darnel intraspecific interference appropriately with a nonlinear fit but caution must be taken in interpretation of estimated Persian darnel fecundity since a nonlinear fit of interspecific interference could not be fit. When the effect of crop density on Persian darnel fecundity is fit using a linear model, interference can be overestimated at high and low crop densities (Cousens et al. 1987). Further research should be conducted with a wider range and more observations of crop density on Persian darnel fecundity for increased precision in estimating Persian darnel fecundity.
Table 14. Parameter \( j \), \( k \), and \( a \) response (Equation 2) to increasing Persian darnel density in spring wheat, canola, sunflower and Persian darnel monoculture. Significant parameter estimates were compared using Bonferroni confidence intervals. Comparisons were determined to be significant at \( P < 0.05 \).

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>df</th>
<th>( t )</th>
<th>( j ) (SE)</th>
<th>Bon. Con. Int.</th>
<th>Bon. Sig(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Monoculture</td>
<td>78</td>
<td>1.16</td>
<td>31615.60 (1.13 ES)</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>159</td>
<td>1.16</td>
<td>35.49 (3.71)</td>
<td>7.35</td>
<td>a</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>159</td>
<td>1.16</td>
<td>97.79 (11.48)</td>
<td>22.73</td>
<td>b</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>78</td>
<td>1.16</td>
<td>218.13 (24.67)</td>
<td>48.85</td>
<td>c</td>
</tr>
<tr>
<td>2001</td>
<td>Monoculture</td>
<td>141</td>
<td>1.16</td>
<td>167.14 (21.97)</td>
<td>43.50</td>
<td>y</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>285</td>
<td>1.16</td>
<td>30.89 (3.3)</td>
<td>6.53</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>285</td>
<td>1.16</td>
<td>49.49 (8.58)</td>
<td>16.99</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>141</td>
<td>1.16</td>
<td>42.86 (4.00)</td>
<td>7.92</td>
<td>x</td>
</tr>
</tbody>
</table>

\(^a\) Parameter estimates compared by year. The letter set (a-c) for 2000 and (x-z) 2001.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>df</th>
<th>( t )</th>
<th>( k ) (SE)</th>
<th>Bon. Con. Int.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Monoculture</td>
<td>78</td>
<td>1.16</td>
<td>51142.27 (2498.89)</td>
<td>4947.80</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>159</td>
<td>1.16</td>
<td>23635.86 (4505.69)</td>
<td>8921.27</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>159</td>
<td>1.16</td>
<td>8998.24 (1066.83)</td>
<td>2112.32</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>78</td>
<td>1.16</td>
<td>38283.72 (30521.65)</td>
<td>NA</td>
</tr>
<tr>
<td>2001</td>
<td>Monoculture</td>
<td>141</td>
<td>1.16</td>
<td>29736.89 (1826.88)</td>
<td>3617.22</td>
</tr>
<tr>
<td></td>
<td>Spring wheat</td>
<td>285</td>
<td>1.16</td>
<td>52312.29 (9417.01)</td>
<td>18645.68</td>
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<tr>
<td></td>
<td>Canola</td>
<td>285</td>
<td>1.16</td>
<td>54973.27 (19975.91)</td>
<td>39552.30</td>
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<tr>
<td></td>
<td>Sunflower</td>
<td>141</td>
<td>1.16</td>
<td>46318.67 (17522.08)</td>
<td>34693.72</td>
</tr>
</tbody>
</table>

\(^a\) Parameter estimates compared by year. The letter set (a-c) for 2000 and (x-y) 2001.

<table>
<thead>
<tr>
<th>Year</th>
<th>Crop</th>
<th>df</th>
<th>( t )</th>
<th>( i ) (SE)</th>
<th>Bon. Con. Int.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Spring wheat</td>
<td>159</td>
<td>1.16</td>
<td>0.004 (0.000)</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>159</td>
<td>1.16</td>
<td>0.005 (0.000)</td>
<td>0.0003</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>78</td>
<td>1.16</td>
<td>0.072 (0.033)</td>
<td>0.0650</td>
</tr>
<tr>
<td>2001</td>
<td>Spring wheat</td>
<td>285</td>
<td>1.16</td>
<td>0.001 (0.000)</td>
<td>0.0001</td>
</tr>
<tr>
<td></td>
<td>Canola</td>
<td>285</td>
<td>1.16</td>
<td>0.001 (0.000)</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>Sunflower</td>
<td>141</td>
<td>1.16</td>
<td>0.024 (0.008)</td>
<td>0.0152</td>
</tr>
</tbody>
</table>

\(^a\) Parameter estimates compared by year. The letter set (a-b) for 2000 and (x-y) 2001.
Figure 24. Effects of crop and Persian darnel density on Persian darnel fecundity (seed/m²) in 2000. Data were fitted to Equation 2. Parameter estimates and regression statistics are shown in Table 14.
Figure 25. Effects of crop and Persian darnel density on Persian darnel fecundity (seed/m²) in 2001. Data were fitted to Equation 2. Parameter estimates and regression statistics are shown in Table 14.
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