University of Alberta

Faba bean and lupin: new Alberta grain legume crops to improve agricultural sustainability

by

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Abstract

Field pea (*Pisum sativum* L.) is the traditional grain legume crop grown in the Parkland region of Alberta; however, tannin-free faba bean (*Vicia faba* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.) may also be productive grain legume crops in the region. A series of experiments were conducted to establish local best management practices for faba bean and lupin, to quantify the grain and forage productivity of new and traditional grain legumes, and to determine grain legume N contributions to Alberta cropping systems.

Forage intercrop mixtures of grain legumes and barley (*Hordeum vulgare* L.) yielded less than, or similar to, barley sole crops. Faba bean-barley, lupin-barley, and pea-barley intercrops had 64%, 27%, and 55% higher protein yields, respectively, than sole crop barley. Pea-barley intercrops offered the most favorable combination of forage DM yield, nutritive value, and economic returns.

Faba bean, lupin, and pea produced maximum seed yields of 7640, 4020, and 6460 kg ha^{-1}, respectively. The absence of weed interference and a high planting density increased grain legume seed and N-fixation yields. In the absence of weed interference, faba bean, pea, and lupin N-fixation yields ranged from 70-223, 78-147, and 46-173 kg N ha^{-1}, respectively. However, the management practices that increased N fixation resulted in only marginal subsequent wheat (*Triticum aestivum* L.) yield increases.

Faba bean and lupin crop residues have the potential to supply more N to subsequent crops than pea crop residues. After approximately 10 months of decomposition, the amount of N released from surface placed and buried

residues, respectively, was: 66 and 64 kg ha^{-1} from barley, 63 and 72 kg ha^{-1} from faba bean, 106 and 131 kg ha^{-1} from lupin, and 37 and 49 kg ha^{-1} from pea.

The N rotational benefits of grain legume crops to subsequent crops were predicted by accounting for N fixation and N export, and measuring soil labile N. However, these methods could not predict plant available N. The increased yield and quality of crops grown on grain legume stubble cannot be primarily explained by changes in soil N availability; therefore, further assessments of non-N rotational benefits are required.

Dedication

To my loving and supportive husband

Shane

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List of Abbreviations

ADF, acid detergent fiber

ADL, acid detergent lignin

CP, crude protein

DM, dry matter

DON, dissolved organic nitrogen

L, linear trend

LPD, legume planting density

NDF, neutral detergent fiber

MBN, microbial biomass nitrogen

Ndfa, nitrogen derived from the atmosphere

NW, nonweedy

PPD, pulse planting density

Q, quadratic trend

RFV, relative feed value

TDN, total dissolved nitrogen

W, weedy

Chapter 1

Introduction

This thesis assesses the potential of faba bean and lupin to improve agricultural sustainability in north central Alberta. Agricultural sustainability has been defined as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered (Tilman et al. 2002). This chapter provides background information and a review of the literature which is relevant to the research in this thesis. The research objectives for Chapters 2 to 5 are outlined at the end of this chapter. Chapter 6 contains a summary and synthesis of the conclusions from this research. The topics presented in this introduction are:

- Grain Legumes in Current Cropping Systems: An Overview
    - Grain Legumes
    - Global Grain Legume Production
    - Western Canada Grain Legume Production
- Grain Legumes for North Central Alberta
    - Field Pea
    - Tannin-free Faba Bean
    - Narrow-leafed Lupin
- Grain Legume Nitrogen Fixation

GRAIN LEGUMES IN CURRENT CROPPING SYSTEMS: AN OVERVIEW

Throughout history, agriculture has focused on one goal: increased production. Today, the productivity goal is often combined with the desire for sustainability (Peoples et al. 1995a). Some studies have found that in order to ensure long term productivity of our agricultural systems, in the face of ecological constrains and socioeconomic pressures, it will be necessary to increase crop diversity in both time and space (Altieri 1995).

Alberta cropping systems are heavily dominated by cereal and canola crops (Table 1-1). The lack of species diversity in our agricultural ecosystems is a concern as these low diversity systems depend on costly, and potentially environmentally damaging, external inputs such as fertilizers and pesticides for continued production. Studies in some ecosystems have found that more diverse cropping systems remain productive under fluctuating environmental constraints and require fewer external inputs (Altieri 1995, Thompson and Starzomski 2007). Increasing the use of nitrogen (N) fixing grain legume species in Alberta crop rotations and intercrops should increase ecological stability, reduce input costs, and improve the subsequent crop performance in Alberta cropping systems.

Table 1-1. Proportion of land seeded to various crop types in Alberta, based on the 10-year average (AAF 2006).

Crop	**% Seeded Acres**
Wheat	28
Other Cereals	29
Canola	16
Grain Legumes	3
Tame Hay[1]	23
Total	99

[1] Tame hay refers to hay lands that have been seeded with nonnative species (Barnes et al.,1995)

Grain Legumes

Grain legumes are the edible seeds of a leguminous plant (Allaby 1992). They comprise a small, but very important, part of the 16,400 species in the legume family. The 60 domesticated grain legumes species are universally known for their nutritional attributes of high protein and, depending on the species, either high starch or oil content (Hedley 2001). Grain legumes that are high in protein and starch are referred to as pulses. The most common pulses are pea, bean, lentil, chickpea and faba bean (SPG 2000).

Global Grain Legume Production

Grain legumes occupy 11% of the world's arable lands (FAO 1993) and are an important source of protein for livestock and mankind, especially in developing countries. They provide approximately 10% of the total dietary protein in the world (SPG 2000). Globally, beans comprise 31% of grain legume production and many different types are grown throughout the world. Pea accounts for 23% of grain legume production with the majority of pea production occurring in Canada and France. Chickpea, faba bean, and lentil account for 15%, 6%, and 5% of grain legume production, respectively.

Western Canada Grain Legume Production

Grain legumes began to play a significant commercial and economic role in western Canada in the 1970s. At this time, a surplus of wheat encouraged farmers to diversify into other cash crops, such as canola, lentil, and pea (SPG 2000). With the registration of lentil and pea herbicides and the development of well-adapted varieties, lentil and pea became commercial crops in western Canada. Grain legume production in western Canada was further encouraged by low cereal commodity prices and new agronomic practices, such as reduced summer fallow, longer crop rotations, continuous cropping, and direct seeding. Grain legumes were beneficial additions to the new crop rotations because of their ability to fix N and break weed and disease cycles.

Although western Canadian grain legume acres have increased since the 1970s, there is still more potential. In Alberta only 3% of the arable land is seeded to grain legumes (Table 1-1). If crop rotations include one grain legume crop every five years, 20% of the arable land would be seeded to grain legumes. Currently, the low acreage may be attributed to few grain legume crop options, lack of producer knowledge, low prices, high input costs, and disease pressure. The Saskatchewan Pulse Growers (2005) indicate that Canada can reliably produce, process, and export enough peas and lentils to satisfy world markets. However, in recent years, high grain legume inventories, combined with the increased value of the Canadian dollar, and high transportation costs have led to record low margins for growers and processors. There is also competition in the commodity market as the United States, Australia, and China continue to increase grain legume production. Western Canada must become more efficient and innovative at supplying, producing, processing, and shipping product to encourage the growth of grain legume acres.

In attempts to increase demand for western Canadian grown grain legumes, Pulse Canada, Saskatchewan Pulse Growers, Alberta Pulse Growers and the Manitoba Pulse Growers are working towards market development. One of the primary objectives is to convey the health benefits of eating grain legumes to the North American public and increase domestic grain legume consumption. These organizations are also attempting to increase use of domestic grain legumes in livestock feed rations. For example, western Canada imported $988M or 3.2M tonnes of high protein soybean products from 2001-2005 to supply protein supplement markets (Statistics Canada 2005).

GRAIN LEGUMES FOR NORTH CENTRAL ALBERTA

Field Pea

Field pea, *Pisum sativum*, was cultivated 9,000 years ago making it one of the world's oldest crops (SPG 2000). Peas are native to Syria, Iraq, Iran, Turkey, Israel, Jordan, and Lebanon, but are now grown in nearly all climatic zones. The most common peas grown in western Canada have a smooth seed, with a green or yellow cotyledon, and are harvested at maturity for food and feed. There are also wrinkled peas which are harvested prematurely and used for canning or freezing. Australian winter pea and maple pea, which are used as livestock feed or in specialty food products, have colored seed coats and flowers.

The pea growing areas of Canada have changed dramatically over the past century. Initially, Ontario led pea production followed by Manitoba (SPG 2000). In the mid-1980's Saskatchewan was the dominant pea producer with Alberta and Manitoba having minimal acreage. In 2007, 75% of the Canadian pea crop was produced in Saskatchewan (SPG 2007). In recent years, pea acreage in the cooler and moister areas of Alberta decreased due to harvestability problems and reduced yields caused by the fungal disease, ascochyta (Lopetinsky, personal communication).

Field pea is a cool season crop that is most productive when it receives timely precipitation during its vegetative and flowering phases (Park and Lopetinsky 1999). Optimum daytime temperatures for field pea are 23°C while optimum night time temperatures are 10°C. The crop is particularly sensitive to drought and high temperatures during flowering when flower blast can occur.

Field pea is a herbaceous plant with a slender succulent stem ranging from 0.3 to 1.8m in height (Park and Lopetinsky 1999). The semi-leafless types are most common. They are characterized by a large stipule, large compound tendrils, and an absence of leaflets. Pea has a fine tap root with well developed laterals and the root system can reach a depth of 80 cm (Biddle et al. 1988). Flowering nodes produce one to three, 4-10 cm long pods, each containing 6-10 seeds weighing between 190 and 260 mg (SPG 2000). Pea seeds contain 20 to 25% crude protein, and have a high lysine content making it an excellent livestock feed.

Tannin-free Faba Bean

The majority of faba beans grown as grain legumes are *Vicia faba* var. *equina* and *Vicia faba* var. *minor* (Knott et al. 1994). Traditional faba bean varieties contain several anti-nutritional factors, including condensed tannins, which greatly reduce their usefulness as a protein source (Marquardt 1983). In 1930, Erith first described faba bean plants with white flowers. These white flowered faba beans contain <0.6% total phenolics compared with the seed of colored flowered faba beans which contain 4-8% total phenolics (Griffiths and Jones 1977). White flowered cultivars have the following characteristics: no pigment on the stipules or anthocyanin on the stem, decreased seed coat weights, higher in vitro digestibility (Crofts et al. 1980), and 0.2% condensed tannins in the testa

(Marquardt et al. 1978). Due to the extremely low levels of condensed tannins, white flowered faba beans are considered tannin-free or zero-tannin, and are an alternative hog feed to soybean meal (Zijlstra et al. 2004).

In the early 1970's, tannin-containing faba bean showed great promise as a crop in western Canada because the seed contained 28% protein and could supply vegetable protein to global markets (Vandenberg et al. 2005). However, high seed costs and anti-nutritional factors, caused interest in faba bean to decline. In 2003, a resurgence in faba bean production began with the registration of the tannin-free variety, 'Snowbird' (CFIA 2003). The lack of anti-nutritional factors, high energy, high protein, high yields, and similar production costs relative to field pea made this crop an attractive option for producers. In 2006, it was estimated that 7000 acres (2755 ha) of 'Snowbird' faba bean were grown in Alberta and acreage is forecasted to increase up to 250,000 acres (98,425 ha) in 2010 due to increased demand from protein supplement markets (Lopetinsky personal communication).

Since faba bean is a relatively new crop in western Canada only a few cultivars are available and the majority of them arose from European breeding programs. Canadian breeding programs began in the 1970s; however, with the decline in the faba bean industry, breeding efforts ceased (Vandenberg et al. 2005). In 2002, with renewed faba bean interest, a small breeding program was initiated at the Crop Development Centre, University of Saskatchewan, to breed faba beans for western Canada. There are two goals for this breeding program. One is to develop a high quality, faba bean for the Egyptian food market and the second is to develop a faba bean for the moist, north and eastern prairies where pea production is unreliable. In both cases, the breeding program is attempting to produce varieties that are early maturing, small seeded, and low in tannin.

Faba beans are suited to cool conditions with optimum average temperatures of 18-27°C over the growing season (Kay 1979). They are sensitive to extremely high and low temperatures during pollination and fertilization (Jellis et al. 1998) which are thought to cause flower abortion. Faba bean water use ranges from 235 to 354 mm when the crop is seeded early (Loss et al. 1997). These high moisture requirements are necessary, as faba beans have a relatively shallow root system and are poorly adapted to drought (Day and Legg 1983). Faba bean production is suited to agroecoregions 10 and 13 of the Northern Great Plains, which are characterized by Black Chernozems and Gray Luviosols (Padbury et al. 2002). These areas have favorable moisture levels and temperatures for faba bean production and the growing season is generally too short or wet for the production of other cool season grain legume crops such as chickpea or lentil.

Faba bean is an annual, upright herb, 60-180cm tall, with a thick, square, hallow stem (Knott et al. 1994). Leaves are alternate-pinnate with two to six oval shaped leaflets (Knott et al. 1994). Faba bean has a tap-root with extensive lateral branching (Kay 1979). Two to six flowers are borne in the reproductive leaf axils on short axillary racemes (Kay 1979, Knott et al. 1994). Flowers can be pure white, purple, or pink. Young pods are green and fleshy with a pointed beak, as the pod matures, it turns brown or black (Kay 1979). Pods contain two to eight seeds which weigh between 400-700 mg and can be cream, buff, red, purple, brown, black, or green depending on the variety (Knott et al. 1994).

Narrow-leafed Lupin

Lupin was domesticated following World War I in response to the need for high protein crops adapted to temperate climates (Gladstones 1998). Lupin domestication required the combination of low alkaloid seed contents with non-shattering pods. Wild lupin seed contains 5-40 g alkaloid kg^{-1} while the domesticated 'sweet' lupin, which is used for human and livestock consumption, contains <200 mg alkaloid kg^{-1} (Petterson 1998). Currently, there are three 'sweet' lupin species grown as high protein, grain legume crops: white lupin (*Lupinus albus*), blue lupin or narrow-leafed lupin (*Lupinus angustifolius*), and yellow lupin (*Lupinus luteus*).

Between 1954 and 1967, narrow-leafed lupin was fully domesticated by John Gladstones in western Australia. This species is native to the Mediterranean and south western France but it is widely grown in Australia, Tasmania, New Zealand, South Africa, northern Europe, and the south eastern United States (Duke 1981). Australian narrow-leafed lupin cultivars do not perform well in Alberta (Blade personal communication). However, recent screening tests with narrow-leafed lupin varieties, from a German breeding program show promise. Two of these varieties, 'Arabella' (CFIA 2005) and 'Rose' (CFIA 2006) were granted plant breeder's rights in Canada.

L. angustifolius is suited for environments with growing seasons of 120-150 days (Römer 2003). This species is more tolerant of acidic conditions than other legume species and prefers soils with a pH between 5.0 and 6.8. Lupin is adapted to well-drained, coarse textured, low fertility soils (Gladstones 1970). Seed yields can be highly variable and limited by the amount and distribution of rainfall (Dracup et al. 1998) and hot temperatures during seed fill (Reader et al. 1997). Diseases, such as anthracnose, have devastated white and yellow lupin crops but narrow-leafed lupin has the advantage of being more disease tolerant than other lupin species (Römer 2005). Narrow-leafed lupin has proven to be the most suitable lupin species for production in Alberta.

As the name suggests, narrow-leafed lupin has spirally arranged, opposite, palmate leaves with 4-9 narrow leaflets (Dracup and Kirby 1996). Plants have a tap-root and a sturdy main stem which develops multiple first order and second order branches. Typically, only the uppermost 2-4 branches develop flowers and set seed. The inflorescence is a raceme and flowers are generally self-pollinated. Narrow-leafed lupin pods are smaller (5 cm long) than other lupin species and contain 4-6 ovoid shaped seeds weighing 145 mg (Perry et al. 1998). Seeds contain 30 to 40% protein, depending on the species (Petterson 1998). The nutritional quality of lupin protein is considered similar to that of soybean and superior to that of other legume species (Gladstones 1970, Waldroup and Smith 1989, Kyle 1994).

GRAIN LEGUME NITROGEN FIXATION

Inorganic N fertilizer is a convenient and relatively cheap source of N to supply crop nutrient demands (Peoples et al. 1995a). However, typically only 18-49% of the applied N fertilizer is used by maize, rice, and wheat crops (Cassman et al. 2002) with the unused portion being lost to water sources and the atmosphere. With growing international concern over global warming, environmental degradation, and loss of natural resources, biological N fixation by grain legumes represents a renewable resource for sustainable agriculture which can partially replace inorganic N fertilizer (Peoples et al. 1995a).

Seventy eight percent of the air we breath is atmospheric N, but plants are unable to take N from the atmosphere and make it into a usable form (Havlin et al. 1999). Legumes have a unique ability to benefit cropping systems by forming a symbiotic association with *Rhizobium*, *Bradyrhizobium,* or *Azorhizobium* bacteria which are able to reduce atmospheric N into ammonia (Hopkins and Hüner 2004). The fixed N may be utilized by the legume host plant, excreted into the soil and used by neighbouring plants, or released into the soil as crop residues decompose (Havlin et al. 1999).

Measuring Nitrogen Fixation

The total amount of N fixed by legume species and the proportion of N derived from the atmosphere (% Ndfa) varies widely (Tables 1-2, 1-3, and 1-4). For a particular legume species, N fixation varies between locations and years due to differences in soil fertility, effectiveness of inoculation, environmental conditions, soil pH, photosynthetic activity, and legume management (Havlin et al. 1999). Estimates of N fixation also vary depending on the method used to calculate N fixation: N-difference method, ^{15}N natural abundance method, ^{15}N isotope dilution method, acetylene reduction method, or the 'A' value method which is a modified ^{15}N isotope dilution method (Cuttle et al. 2003). There is no superior method to measure N fixation and each method has advantages and disadvantages. Although isotope based techniques are advocated by Unkovich and Pate (2000), they indicate these methods still have their limitations. Measurements of N fixation can be misleading because most methods do not account for N in the roots or stubble (Evans et al. 2001). Based on current methods, it is impossible to obtain accurate measurements of fixed N and, due to differences in measurement techniques, it is difficult to compare results from multiple studies.

Reported N fixation values and percent N derived from the atmosphere (% Ndfa) for faba bean, narrow-leafed lupin, and field pea are given in Tables 1-2, 1-3, and 1-4, respectively. The referenced studies are conducted in a range of growing environments, with different cultural practices, and with different methods of measuring fixation. Based on these studies, faba bean N fixation varies between 8-352 kg N ha^{-1} yr^{-1}, lupin fixation varies from 95-283 kg N ha^{-1} yr^{-1}, and pea fixation varies from 33-246 kg N ha^{-1} yr^{-1}. In spite of the numerous studies, there is still uncertainty about the proportion and quantity of N fixed by each grain legume species.

Table 1-2. Estimates of % Ndfa and the quantity of N fixed by faba bean, *Vicia faba*.

% Ndfa	**N Fixation (kg N ha^{-1} yr^{-1})**	**Growing Environment**	**Reference**
72-92	78-181	France and Syria; local cultural practices; 20-100 kg N fertilizer ha^{-1}; above ground N only	Beck et al. 1991
60-94	82-249	Central Alaska; 20 kg N fertilizer ha^{-1}; above ground N only	Sparrow et al. 1995
60-70	150-202	Denmark; 40-60 plants m^{-2}; 50kg N fertilizer ha^{-1}; above ground N only	Jensen 1986
n/a	165-240	Germany; no N fertilizer; above ground N only	Maidl et al. 1996
13-96	8-352	Northern New South Wales, Australia; commercial crops; above and below ground N	Rochester et al. 1998
88	n/a	Northern Great Plains of Canada and the United States; compilation of 10 observations from research studies	Walley et al. 2007

Table 1-3. Estimates of % Ndfa and the quantity of N fixed by narrow-leafed lupin, *Lupinus angustifolia*.

Ndfa (%)	**N Fixation** (kg N ha^{-1} yr^{-1})	**Growing Environment**	**Reference**
87	247	South-eastern Australia; 45-50 plants m^{-2}; no N fertilizer; above ground N only	Armstrong et al. 1997
69-72	174-177	Northern New South Wales, Australia; commercial crops; above and below ground N	Rochester et al. 1998
74-93	95-283	Southwest Australia; commercial crops; above ground N	Unkovich et al. 1995

Table 1-4. Estimates of % Ndfa and the quantity of N fixed by field pea, *Pisum sativum*.

% Ndfa	N Fixation (kg N ha^{-1} yr^{-1})	Growing Environment	Reference
53	104	South-eastern Australia; 45-50 plants m^{-2}; no N fertilizer; above ground N only	Armstrong et al. 1997
63-72	33-126	France and Syria; local cultural practices; 20-100 kg N fertilizer ha^{-1}; above ground N only	Beck et al. 1991
35-90	42-144	Central Alaska; 20 kg N fertilizer ha^{-1}; above ground N only	Sparrow et al. 1995
44-64	102-215	Denmark; 80 plants m^{-2}; 50kg N fertilizer ha^{-1}; above ground N only	Jensen 1986
n/a	215-246	Germany; no N fertilizer; above ground N only	Maidl et al. 1996
74-85	123-205	Northern New South Wales, Australia; commercial crops; above and below ground N	Rochester et al. 1998
60-91	54-165	Southwest Australia; commercial crops; above ground N	Unkovich et al. 1995
55	n/a	Northern Great Plains of Canada and the United States; compilation of 79 observations from research studies	Walley et al. 2007

Maximizing Nitrogen Fixation

Havlin et al. (1999) indicates that soil pH, mineral nutrient status, photosynthetic activity, and climate are the most important factors influencing nitrogen fixation. Soil acidity can restrict *Rhizobia* growth and survival while high levels of soil mineral N and factors which reduce photosynthetic rates will reduce N fixation. Peoples et al. (1995b) reviews the literature on the effects of plant and soil management on legume N fixation. Nitrogen inputs from biological N fixation can increase by increasing % Ndfa and/or by increasing legume growth which will increase total N requirements. A survey of N fixation in farmer's fields found that levels of N fixation are only a fraction of the theoretical limits that can be achieved under optimal conditions (Peoples et al. 1995a). Levels of % Ndfa may be enhanced by maximizing the numbers and effectiveness of *Rhizobia* bacteria, reducing soil nitrate levels, and reducing legume and *Rhizobia* sensitivity to high soil nitrate levels (Peoples et al. 1995b). To increase legume N demands, strategies need to be employed which maximize legume growth. Other means of enhancing N fixation include *Rhizobial* strain selection, inoculant technology, and genetic manipulation of the legume host.

Competition Effects on Nitrogen Fixation

The literature relating to plant competition effects on N fixation comes from intercropping and weed interference studies. A number of intercropping studies report that legume % Ndfa and total N fixation are affected by interspecific plant competition for resources (Cuttle et al. 2003). Danso et al. (1987) indicates that greater competition for soil N, due to greater plant populations in faba bean-barley intercrops, substantially increases % Ndfa; however, the faba bean-barley intercrop fixes less total N than the sole crop faba bean. Hauggaard-Nielsen et al. (2001) reports a similar trend in pea-barley intercrops with higher % Ndfa in the intercrop but significantly less total N fixation in comparison to the sole pea crop. Similarly, Izaurralde et al. (1992) reports that % Ndfa is 39% higher in pea-barley intercrops than in sole-cropped pea. Geijersstam and Mårtensson (2006) also note that intercropping pea with oat (*Avena sativa* L.) increases % Ndfa in comparison to pure pea stands. Weed removal increases the total amount of N fixed by several legume species (Keatinge et al. 1988). Soon et al. (2004) reports that delaying weed removal, with herbicides, increases % Ndfa in a pea crop but there is no effect on total N fixation. These studies indicate that competition from non-legumes consistently increases %Ndfa but the effects on total N fixation are variable.

GRAIN LEGUMES IN CROPPING SYSTEMS

Globally, there is a significant shift towards simplifying agroecosystems (Vandermeer et al. 1998). However, a number of authors agree that cropping system diversity is essential for sustainable agriculture (Altieri 1987, Swift and Ingram 1996, Beckie et al. 2006). Enhanced biodiversity in some agroecosystems provides the systems with a number of ecological services including control of local microclimate, nutrient cycling, regulation of local hydrological processes, regulating pest populations, and detoxifying noxious chemicals (Altieri 1995). Loss of these ecological services can burden producers with additional input costs and reduce the public's quality of life when soil, water, air and food quality are diminished due to pesticide and or nitrate contamination.

Increased use of grain legumes in crop rotations and annual intercrops are simple, but underutilized, methods of increasing species diversity in modern cropping systems and reducing N fertilizer use. Historically, legumes have been essential cropping system components which supply N, but readily available, and inexpensive, N fertilizer has reduced agriculture's dependence on legumes (Havlin et al. 1999). As inorganic N fertilizer becomes more expensive, due to higher manufacturing and transport costs, there is renewed interest in the use of legumes to supply a portion of the N to the cropping system.

Grain Legumes in Intercrops

Today, the majority of modern cropping systems are dominated by monocultures that have low spatial diversity (also referred to as alpha diversity which indicates the biodiversity within a community or ecosystem), reduced species interactions in a growing season, and depend on costly external inputs for continued production (Altieri 1995). Crop mixtures, generally referred to as intercrops (Anil et al. 1998) can provide numerous benefits to cropping systems through increasing total yield and land use efficiency, improving yield stability, enhancing light, water, and nutrient use, and controlling weeds, insects, or diseases (Willey 1979a). In temperate climates, intercropping is more successful when used for forage production than grain production (Anil et al. 1998).

The inclusion of grain legumes in intercrops can reduce the need for N fertilizer in forage production (Geijersstam and Mårtensson 2006). Intercropping legumes with cereals may also minimize the N losses commonly associated with legume sole crops through cereal uptake of soil inorganic N and slower N mineralization during decomposition, due to higher cereal C:N ratios (Hauggaard-Nielson et al. 2003). Previous studies note that the inclusion of grain legumes in forage intercrops increases protein yields (Walton 1975, Berkenkamp and Meeres 1987, Anil et al. 1998), and improves forage nutritive value (Chapko et al. 1991, Carr et al. 1998).

The management objective of intercrops is to minimize competition and maximize complementary interactions between species (Willey 1979b). Properly managed intercrops are more productive than monocultures because there is better resource use over time (Natarajan and Willey 1980) and space (Reddy and Willey 1981). For example, intercrops can take up nutrients (Willey 1979b) and water (Francis 1989) from a larger soil volume if intercrop species have different rooting habits and rooting depths. Differences in peak demand for nutrients, by the intercrop components, (Willey 1979b) and greater improvement in light utilization can also improve productivity. Reductions in pest outbreaks are attributed to intercrops having a mixture of susceptible and resistant plants which may restrict the spread of the pest (Altieri and Liebman 1986).

Grain Legumes in Crop Rotations

The primary means of increasing temporal species diversity in cropping systems is to employ crop rotations, in which different crops are grown, in succession, on the same land. Millington et al. (1990) notes the elements of successful crop rotations: balance fertility building and exploitative crops, include a legume, include crops with different root systems, separate crops with similar pest and disease susceptibility, vary weed susceptible with weed suppressing crops, employ green manure crops, include winter soil cover, and increase soil organic matter. Millington et al. (1990) suggest rotations should include legumes with cereals, long-season crops with short season crops, perennials with annuals, and summer annuals with winter annuals.

Nitrogen Rotational Benefits of Grain Legumes

Higher grain and N yields of cereal crops, grown on legume stubble, are frequently reported. Peoples and Herridge (1990) report 16-353% higher cereal yields on grain legume stubble in comparison to cereal yields on non-legume stubble. In addition to increased grain yields, cereals following grain legumes typically have increased protein contents (Marcellos 1984, Wright 1990a,b, Campbell 1992, Zentner et al. 2001).

Increased yields following grain legume crops are partially attributed to increased soil N levels. In a review, Peoples et al. (1995a) report that soil nitrate-N levels following legumes are 14-77 kg N ha^{-1} greater than levels following non-legume crops. The increased nitrate is attributed to: N-sparing by the grain legume (Chalk 1998, Evans et al. 1991, Herridge et al. 1995); N mineralization from senesced legume leaves, roots, or nodules (Peoples et al. 1995a); and rhizodeposition which involves the release of biologically fixed N products from nodulated roots (Sawatsky and Soper 1991, Mayer et al. 2004).

Despite many reports of increased total soil nitrate levels following grain legumes, increases in total soil N are not always detected (Peoples et al. 1995a). Some explanations for low total soil N levels following annual legume crops include: (i) N removal in harvested grain, (ii) single legume crops may not result in detectable or significant changes in total soil N levels, and (iii) N released from decomposing legume crop residues can be susceptible to loss or it may be tied up in various forms of soil organic matter.

Haynes et al. (1993) notes that more than 70% of total plant N is contained in the harvested seed of grain legumes while Armstrong et al. (1997) notes that 41-75% of total plant N is removed from the field in the harvested grain. For legumes to make a positive contribution to soil N, levels of N fixation must exceed the amount of N removed in the grain. Soil N levels are further reduced if legume straw residues are also removed from the field.

Campbell et al. (1992) indicates that the N supplying power of the soil in a wheat-lentil rotation is enhanced compared to monoculture wheat rotations only in the last 5 years of a 12 year study. Other authors are unable to document increases in soil microbial N in soils previously planted to grain legumes compared to soils previously planted to cereals (Stevenson and van Kessel 1996, Soon and Arshad 2004).

In Denmark, Jensen (1994a) reports that 9-17% of the input ^{15}N from pea residues has leached as nitrate below a 45-cm soil depth in the first 180 days of decomposition. The majority of N released from decomposing crop residues is found in soil microbial biomass and recalcitrant soil organic matter (Jensen 1994a, Mayer et al. 2004). In this form, the N can be gradually mineralized for use by future crops and can increase long-term soil fertility (Kumar and Goh 2002).

Many studies have attempted to quantify the contribution of biologically fixed N to subsequent crops. However, there is no superior method to measure N rotational benefits and each method has advantages and disadvantages. The legume N rotational benefit is often equated to the N fertilizer replacement value to the subsequent crop (Stevenson and van Kessel, 1996) or the N-fertilizer equivalence. The 'N-sparing effect', or the amount of soil mineral N not used by the legume, can be determined by measuring the additional amount of mineral N in the soil after growing a legume crop as compared to a non-legume crop. Nitrogen released from decomposing legume residues can be measured in mesh litterbags (Ibewiro et al. 2000). The A-value can be used to estimate the amount of available soil N remaining after a legume crop (Stevenson and van Kessel 1996). With this method, ^{15}N fertilizer is applied to legume and cereal stubble. A subsequent crop grown on the legume stubble would be expected to have a lower ^{15}N concentration, compared with a subsequent crop grown on cereal stubble, as it would be taking a portion of its N from the previous legume crop. Nitrogen availability can be estimated directly by applying ^{15}N labeled legume residues to the soil and then measuring the ^{15}N concentration of the subsequent crop (Jensen 1994b). Rennie and Rennie (1983) indicate that it is difficult to obtain a soil sample which will give a representative measure of available soil N over the entire growing season. They suggest the best estimation of plant available soil N is to allow a plant to sample for itself.

Non-Nitrogen Rotational Benefits of Grain Legumes

In many instances, N fertilizer applications to a crop grown on cereal stubble are unable to make yields equal to those obtained on grain legume stubble (Wright 1990a, Rowland et al. 1994). In these situations, a portion of the increased yield is attributed to increased soil N but the other portion is attributed to non-N benefits. Research conducted in Saskatchewan, by Stevenson and van Kessel (1996), found that only 8% of the field pea rotational benefit is explained by additional soil N and the remaining 92% is attributed to non-N factors: reduced root and leaf diseases, reduced weed pressure, increased phosphorous (P), potassium, sulfur availability, improved soil structure, and growth substances released from the grain legume residue. Other studies indicate that 29% of the legume rotational benefit is attributed to non-N effects (Janzen and Schaalje 1992).

There are a number of factors which may explain non-N benefits. Following a grain legume crop, *Rhizobia* bacteria can be found colonizing the roots of non-legume crops. This colonization is associated with increased yields of the non-legume (Yanni et al. 2001, Lupwayi et al. 2004a). The increased yield does not appear to be associated with N fixation (Yanni et al. 2001) but rather diazotropic bacteria (N fixing bacteria) stimulating plant growth, improving resistance to environmental stress, and increasing disease resistance (Dobbelaere et al. 2003).

Soil H_2 fertilization may be a non-N legume rotational benefit. A byproduct of the N fixation process is H_2 (Hopkins and Hüner 2004) which can account for 33% of the energy demands of the N fixation process (Hunt and Layzell 1993). It is thought that the excess H_2 gas enhances the growth of H_2-oxidizing soil microorganisms (Dong and Layzell 2001). Dong et al. (2003) hypothesizes that the altered soil microflora community structure may influence plant growth by the soil microflora providing 'plant available' nutrients, increasing the uptake of mineral nutrients, and protecting plants against pests and diseases (Glick 1995).

Legumes can mobilize soil-bound P and may produce P rotational benefits (Nuruzzaman et al. 2005, Kamh et al. 1999, Horst et al. 2001). Legumes are thought to enhance P uptake by mobilizing soil-bound P through root exudates and producing large root systems (Nuruzzaman et al. 2005). The P benefits are attributed to mineralization of legume roots which have high P contents, rather than legume root exudates creating long-term changes in soil chemistry.

Legumes are also known for their ability to ameliorate soil structure (Bullock 1992, Karlen et al. 1994). For example, lupins are thought to aid in erosion control and improve soil structure (Bayliss and Hamblin 1986) by increasing soil organic matter. Increased organic matter reduces soil bulk density and improves water-stable aggregates in fine textured soils (Reeves et al.

1984). The deep tap-root of narrow-leafed lupin grows well in heavily compacted soils where it acts as a 'biological plough' to reduce soil compaction (Henderson 1989). The reduction in soil compaction greatly benefits subsequent cereal crops as cereals have thin fibrous roots and their growth is impeded on compacted soils.

Legumes in rotation can use less water than cereals and may leave more soil moisture for subsequent crops. Studies at Swift Current, SK, indicate that dry bean and dry pea stubble hold more post-harvest soil water than wheat stubble, which may partially account for higher yields on bean and pea stubble (Miller et al. 2002). In dry years, Miller et al. (2003) reports greatest wheat yields on pea stubble; intermediate wheat yields on lentil, mustard and wheat stubble; and lowest yields on desi chickpea stubble. This response is positively correlated with soil water use by the subsequent wheat crop. However, under conditions of severe drought, when water is the largest constraint to growth, differences in N and non-N factors do not influence growth (Havlin et al. 1999).

Although not specific to legumes, diverse crop rotations are thought to reduce the incidence of insects, weeds, and diseases by breaking the pest life cycle (Altieri 1995). The most effective breaks in pest cycles are achieved when successive crops of the same species are avoided, crops with common pests are not grown in succession, and when extremely different plant species follow each other in sequence.

GRAIN LEGUME – SOIL MICROBE – SUBSEQUENT CROP NITROGEN CONTINUUM

Grain Legume Nitrogen in Crop Residues

Many N rotational benefits are realized after legume crop residues have decomposed. In the decomposition process, soil microorganisms mineralize organic compounds and make nutrients available for subsequent crop uptake (Soon and Arshad 2002). In addition, returned crop residues improve soil water retention, protect against soil erosion, and increase soil organic matter (Kumar and Goh 2000). The rate and pattern of decomposition and subsequent nutrient release are regulated by the residue quality, the decomposer community, and the physiochemical environment (Couteaux et al. 1995, Cadish and Giller 1997).

In general, residues with a high N concentration display enhanced decomposition and N mineralization (Janzen and Kucey 1988). High C:N ratios are negatively correlated with decomposition and N mineralization (Ranells and Wagger 1996) as is lignin content, lignin:N ratio, polyphenol content, and polyphenol:N ratio (Paul and Clark 1996, Kumar and Goh 2000). Grain legume crop residues typically have low C:N ratios between 25:1 to 40:1 (Stevenson and van Kessel 1996) and this generally results in rapid mineralization and significant increases in soil mineral N (Karlen et al. 1994).

Most estimates of the grain legume N contribution, to the cropping system, are based solely on aboveground plant biomass, even though most aboveground N is removed in harvested grain and/or straw (Evans et al. 2001, van Kessel and

Hartley 2000). Russell and Fillery (1996) report that lupin root N represents 28% of total plant N, Armstrong et al. (1994) notes that pea root N represents 7-10% of total plant N at maturity, while Khan et al. (2003) estimate faba bean and barley roots contain 24% and 36% of total plant N, respectively. In addition to root N, Mayer et al. (2003) indicates N rhizodeposition, which consists of low and high molecular weight compounds released or sloughed off by the roots, constitutes 12-16% of total plant N. Although there are no simple or proven methods for measuring root and rhizodeposition N, it is important to consider these N sources when determining residual N contributions to subsequent crops.

Grain Legume Nitrogen in Soil Microbes

Soil microbes comprise the portion of soil organic matter that regulates the transformation and storage of nutrients (Horwath and Paul 1994). This labile portion represents 1-3% of the total soil C and 5% of the soil N (Smith and Paul 1990). The size of the microbial community can be estimated with a variety of methods: chloroform fumigation-incubation, chloroform fumigation-extraction, substrate-induced respiration, and phospholipid fatty acid analysis. The standard method for determining microbial biomass is the chloroform fumigation-extraction method.

There are reports of legume based crop rotations enhancing soil microbial biomass (Lupwayi et al. 1999) and diversity (Lupwayi et al. 1998, Biederbeck et al. 2005). In Denmark, during the initial decomposition of incorporated pea residues, Jensen (1994a) reports that microbial biomass N (MBN) almost doubled. In the following spring, MBN peaked and then fell to initial levels after 1yr of decomposition. In Saskatchewan, Stevenson and van Kessel (1996) recovered 63% of the ^{15}N, from labeled pea residues, in the microbial biomass in the spring following residue incorporation. They also note that microbial biomass recovers more ^{15}N than the succeeding wheat crop. Mayer et al. (2003) indicates that N in a subsequent wheat crop arose from grain legume N that was temporarily immobilized in the soil microbial biomass. Although soil microbial biomass is rarely investigated in studies attempting to quantify the rotational benefits of grain legume crops, the above studies indicate the importance of this factor for short term N storage.

Grain Legume Nitrogen in the Subsequent Crop

According to Jensen and Haahr (1990) the amount of N available to the subsequent crop depends on: the amount of soil mineral N not used by the legume crop; the amount, chemical composition, and mineralization rate of legume residues; the N uptake timing and requirements of the subsequent crop; and the denitrification and leaching N losses.

The N contribution of grain legumes to subsequent crops is often smaller than expected (Stevenson and van Kessel 1996). For example, only 2 to 15% of ^{15}N originally present in pea or lentil crops is accumulated in subsequent cereal crops (Bremer and van Kessel 1992, Jensen 1994b). Similar trends are observed in greenhouse studies where 8.6 to 12.1% of the residual N at maturity is recovered by subsequent wheat and oilseed rape crops (Mayer et al. 2003).

The remaining legume N is stabilized in organic forms in the soil or lost through volatilization, denitrification, or leaching (Bremer and van Kessel 1992). Such low rates of legume N recovery suggest that legumes are an inefficient N source; however, Crews and Peoples (2005) conclude that legume N is generally less susceptible to loss than fertilizer N.

Synchronizing subsequent crop N uptake with legume N mineralization can help to minimize the amount of mineralized N which is lost to water sources and the atmosphere (Crews and Peoples 2005). In legume based systems, asynchrony is greatest when an off-season fallow period follows a legume plow-down or crop harvest (Jensen 1994b). Strategies, such as increasing plant N demand, manipulating N supply, and capturing excess inorganic N, can be used to increase synchrony (Crews and Peoples 2005). In legume based systems this involves changing the timing or placement of residues (Lupwayi et al. 2004b), using legumes with differing residue quality (Ranells and Wagger 1992, Iberwiro et al. 2000), or mixing legume residues with other residue types to affect rates of decomposition and mineralization (Ranells and Wagger 1996, Sarrantonio 2003).

HYPOTHESIS STATEMENT AND OBJECTIVES

The null hypothesis of this thesis is:

The forage intercrop yield and quality, N fixation capability, N supply potential, and rotational benefits of tannin-free faba bean (*Vicia faba* L.) and narrow-leafed lupin (*Lupinus angustifolius* L.) are the same as those of field pea (*Pisum sativum* L.), the traditional pulse crop of the Parkland region of Alberta.

The overall objective of this study is to investigate the potential of new grain legumes, tannin-free faba bean and narrow-leafed lupin, in Alberta cropping systems by establishing local basic best management practices, by quantifying their productivity, by determining their potential N contributions to Alberta cropping systems, and by assessing their potential rotational benefits in Alberta cropping systems. The specific objectives of the research presented in this thesis are:

1. To determine if grain legume crop management practices can affect the productivity of a subsequent wheat crop. (Chapter 3: Weed Interference, Grain legume Species, and Plant Density Effects on Rotational Benefits)

2. To determine the feasibility of faba bean-barley, lupin-barley, and pea–barley intercrops for forage production in the Parkland region of Alberta, Canada. (Chapter 2: Forage potential of intercropping barley with faba bean, lupin, or field pea)

3. To quantify the role different grain legume crops and reduced tillage can play in supplying biologically fixed N to subsequent crops. (Chapter 4: Long-term N release from faba bean, lupin, pea, and barley crop residues)

4. To obtain a quantitative measure of the effects tannin-free faba bean and narrow-leafed lupin have on Alberta soil fertility. (Chapter 5: The role of N in grain legume-wheat cropping sequences)

It should be noted that data for this thesis came from one large experiment. Pulse crop seed yield and subsequent crop yield and quality data from all treatments, and site years, were used in the data set for Chapter 3. Pulse crops seeded with barley, as a model weed, demonstrated potential as annual forage intercrops, and this led to assessing forage yield and quality parameters of pulse-barley mixtures at all six site years (Chapter 2). More data was collected from the Barrhead site, than the Devon or Lacombe sites. The additional data collection from Barrhead was used in Chapters 4 and 5 of the thesis. Straw residues used in the decomposition study (Chapter 4) were collected from four treatments (barley, pea, faba bean, and lupin sole crops) in the large study. These same four treatments had extensive soil sampling and plant tissues from these treatments were analyzed for ^{15}N natural abundance. This detailed data set was complied for use in Chapter 5.

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Chapter 2

Forage potential of intercropping barley with faba bean, lupin, or field pea

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Chapter 2

Forage potential of intercropping barley with faba bean, lupin, or field pea

INTRODUCTION

Intercropping can provide numerous benefits to cropping systems through increasing total yield and land use efficiency, improving yield stability, enhancing light, water, and nutrient use, and controlling weeds, insects, or diseases (Willey, 1979a). In temperate climates, intercropping has been more successful when used for forage production than grain production (Anil et al., 1998).

Intercrops of multiple cereal species have been tested for forage potential in western Canada. Baron et al. (1992) found the nutritive value of spring-winter cereal mixtures to be consistently superior to sole spring crops. Jedel and Salmon (1994) reported yield stability and increased nutritive value in triticale (x *Triticosecale* spp.)–barley and triticale–oat (*Avena sativa* L.) mixtures compared to cereal sole crops. Juskiw et al. (2000) reported that various mixtures of barley, oat, triticale, and rye (*Secale cereale* L.) displayed extended harvest periods and had better forage nutritive value, as measured by neutral detergent fiber (NDF) and acid detergent fiber (ADF), compared to sole crops.

The inclusion of grain legumes in forage intercrops can provide a more sustainable source of N to cropping systems through biological N fixation (Crews and Peoples, 2004). Intercropping legumes with cereals may also minimize N losses commonly associated with legume sole crops through uptake of soil inorganic N by the cereal and slower N mineralization during decomposition, due to higher cereal C:N ratios (Hauggaard-Nielson et al., 2003). In previous studies, the inclusion of grain legumes in forage intercrops has increased protein yields (Walton, 1975; Berkenkamp and Meeres, 1987; Anil et al., 1998), and improved forage nutritive value (Chapko et al., 1991; Carr et al., 1998).

Traditionally, field pea has been the only grain legume crop grown in the Parkland region of Alberta, Canada. However, since 2002 tannin-free faba bean production has increased due to its lack of anti-nutritional factors, high energy, high protein, high yields, and similar production costs relative to field pea. A second cool-season grain legume crop, low-alkaloid, narrow-leafed lupin is also showing promise as a new crop in the region. Previous studies conducted in the United Kingdom (UK), reported narrow-leafed lupin whole crop forage DM yields of 6.6 to 8.4 Mg ha^{-1} and crude protein (CP) concentrations more than 190 g kg^{-1} DM (Fraser et al., 2005). By comparison, maximum faba bean and pea forage DM yields and CP concentrations of 7.8 and 6.2 Mg ha^{-1} and 180 and 157 g kg^{-1}, respectively, were reported in the UK (Fraser et al., 2001). The moderate yields and high CP concentrations of these grain legume crops make them candidates for inclusion in legume-barley forage intercrops.

Although pea–cereal intercrops have been frequently studied (Berkenkamp and Meeres, 1987; Chapko et al., 1991; Jedel and Helm, 1993; Carr et al., 1998, 2004; Mustafa and Seguin, 2004) few studies have tested faba bean–cereal (Berkenkamp and Meeres, 1987; Jedel and Helm, 1993; Ghanbari-Bonjar and Lee, 2003) or lupin–cereal intercrops (McKenzie and Spaner, 1999; Carruthers et al., 2000; Azo et al., 2006). We are not aware of any previous studies that have compared these three cool-season grain legume species grown in mixtures with cereals.

Legumes are often less competitive than cereal species and may require higher planting densities relative to cereals to achieve intercropping benefits. Carr et al. (1998) tested three pea planting densities (40, 80, 120 seeds m^{-2}) in intercrop combinations with various planting densities of barley and oat (93, 185, 278 seeds m^{-2}) for forage production. Due to the high cereal densities, no significant DM or N yield benefits were observed as the intercrops were heavily dominated by the cereal component. In intercrop studies for grain production, Izaurralde et al. (1990) tested three pea planting densities (25, 50, 75 plants m^{-2}) with three barley planting densities (86, 172, 258 plants m^{-2}). Grain, straw, and DM yields of intercropped mixtures increased with increasing the pea planting density. Different trends in the above studies may be related to the competitiveness of the species and varieties used in each study.

The objective of this study was to determine the feasibility of faba bean-barley, lupin-barley, and pea–barley intercrops for forage production in the Parkland region of Alberta, Canada. Two questions were being addressed. Are grain legume–barley forage intercrops a viable option for producers in the Parkland region of Alberta, Canada, compared to traditional barley sole crops for forage production? Which grain legume species and planting densities maximize forage DM yield, nutritive value, and economic returns in an intercrop forage system?

MATERIALS AND METHODS

Site Characteristics

Field experiments were conducted in 2004 and 2005 at three sites representing the Parkland region of central Alberta, Canada. The first site was located on a commercial farm near Barrhead, AB (54°6' N, 114°17' W), and was classified as an orthic humic Gleysol (mesic Typic Endoaquoll) with a heavy clay texture. Rainfall and temperature data were collected from an Environment Canada weather station located 11.4 km from the test site at 54°5' N, 114°21' W. The second site was on a commercial farm near Devon, AB (53°26' N, 113°41' W). Soil at this site was classified as an orthic Black Chernozem (Typic Cryoboroll) with a silty clay loam texture. An Environment Canada weather station (53°19' N, 113°34' W), located 9.1 km from the test site, was used to monitor rainfall and temperature data. The third site was at the Agriculture and Agri-Food Canada Research Centre in Lacombe, AB (52°27' N, 113°44' W), on a thin orthic Black Chernozem (frigid Typic Haplustoll) with a clay loam texture. At this site, an on-site weather station was used to collect rainfall and temperature data. Experiments were seeded into canola (*Brassica napus* L.) stubble at Devon and Lacombe in 2004, tilled grass hay (mixed species) at Barrhead in 2004, and cereal stubble in 2005. Preseeding soil characteristics and soil nutrient analysis are presented in Table 2-1.

In 2004, seasonal mean temperatures from 1 May to 31 August ranged from 12.6 to 12.8°C, depending on the site, and were slightly cooler than the 30-

yr average of 14.0°C at Devon, and 13.7°C at Barrhead and Lacombe. In 2005, seasonal mean temperatures were slightly cooler than the 30-yr average and ranged from 12.8 to 13.5°C depending on the site. Soil water content by weight, to 15-cm depth, averaged over 2004 and 2005, was higher at Barrhead (28%) and Devon (31%) compared with Lacombe (20%), prior to seeding. At Barrhead, rainfall for 1 May to 31 August was less than the 30-yr average (300 mm) in 2004 (276 mm) and 2005 (256 mm). At Devon, rainfall for 1 May to 31 August was similar to the 30-yr average (292 mm) in 2004 (301 mm) but less in 2005 (263 mm). Rainfall for 1 May to 31 August at Lacombe was less than the 30-yr average (299 mm) in 2004 (249 mm) and 2005 (247 mm). Overall, the study was conducted under slightly cooler and drier conditions than the 30-yr average, at all sites.

Experimental Design and Plot Management

Treatments in this study were a subset of treatments from a larger study. The experimental design for the current study was a split-plot randomized complete block design with four blocks. Legume species was the main plot and legume planting density (LPD) was the subplot. Barley sole crops were included in the experimental design of the current study. Snowbird tannin-free (11 g tannin kg^{-1} seed) faba bean, Arabella low-alkaloid (200 mg alkaloids kg^{-1} seed) narrow-leafed lupin, and Cutlass field pea were intercropped with Niobe barley. Barley was planted at right angles to the legume, and seeded at 0.25x (53 plants m^{-2}) the recommended barley sole crop target plant population (210 plants m^{-2}) to create legume-barley intercrops. The barley planting density was selected in attempts to create an intercrop that was not heavily dominated by either species. Legume planting densities represented 0.5, 1.0, 1.5, and 2.0x the recommended sole crop plant population for each legume species in the Parkland region of Alberta, Canada. Recommended populations for faba bean, lupin, and pea are 45, 100, and 75 plants m^{-2}, respectively (Alberta Agriculture and Food, 2001) (Appendix 1-7). The barley sole crop was seeded to meet the recommended target plant population of 210 plants m^{-2} (Alberta Agriculture and Food, 2001) and represented the typical cereal forage crop grown in the Parkland region of Alberta, Canada (Alberta Agriculture and Food, 2006). Mean faba bean emergence was 98% of expected (range 77 - 123%), mean lupin emergence was 76% of expected (range 36 - 132%), mean pea emergence was 97% of expected (range 82 - 117%), mean barley emergence was 70% of expected (range 52 - 83%). This resulted in pea-barley and faba bean-barley intercrops having a slightly higher legume content than was initially intended.

Experiments were seeded 3 May 2004 and 4 May 2005 at Barrhead, 4 May 2004 and 2 May 2005 at Devon, and 13 May 2004 and 3 May 2005 at Lacombe. Individual subplots were 2.4 by 6 m. Legumes were seeded in 12 rows with a small-plot-hoe drill at 20-cm row spacing. For each legume species, peat-based-granular inoculant, containing the appropriate *Rhizobium* bacteria, was placed in the furrow. All legumes were seeded at the same depth, with actual depths varying between 5 and 7.5 cm, depending on soil moisture conditions. Immediately after seeding the legume, barley was cross-seeded with a 3.05-m wide hoe-press drill (Model 9450, John Deere, Deere and Company, Moline, IL) at a depth of 2 to 3.5 cm and a row spacing of 17.5 cm, which did not interfere with legume seed placement.

Phosphorous (triple superphosphate), K (potassium chloride), and S (elemental sulfur) were applied to all treatments in the spring based on soil test recommendations for a 4.57 Mg seed ha^{-1} pea grain crop. To avoid negative effects of fertilizer applications on seedling emergence, up to 118 kg ha^{-1} fertilizer was side-banded 2.5 cm from the seed row. If fertilizer recommendations exceeded this, the remaining fertilizer was broadcast and incorporated with harrows.

Before seeding in 2004, triallate [S-(2,3,3-trichloroallyl)diisopropylthiocarbamate] at 1.7 kg a.i. ha^{-1} was applied and appropriately incorporated to control wild oat (*A. fatua* L.) in all site years with the exception of Lacombe, where glyphosate [*N*-(phosphonomethyl)glycine] at 440 g a.i. ha^{-1} was applied to control early emerged weeds. To control heavy weed pressure at Devon, glyphosate at 440 g a.i. ha^{-1} and MCPA [(4-chloro-2-methylphenoxy)acetic acid] at 300 g a.i. ha^{-1} were applied before crop emergence. After crop emergence, broadleaf weeds in the faba bean–barley, pea–barley, and sole crop barley were controlled with an initial application of bentazon [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] at 1.1 kg a.i. ha^{-1} in 240 L ha^{-1} of water at 275 kPa when the legumes were at the 3 to 4 node stage. At Devon and Barrhead, there were no in-crop herbicide applications on lupin. At Lacombe, metribuzin [4-amino-6-(1,1-dimethylethyl)-3-

(methylthio)-1,2,4-triazin-5(4*H*)-one] was applied at 203 g a.i. ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa 2 wk after bentazon, on all treatments. In 2005, broadleaf weeds were controlled with two applications of metribuzin at 138 g a.i. ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa, 10 d apart. At Lacombe only one metribuzin application was made. At all sites wild oat was controlled with an application of tralkoxydim (2-[1-(ethoxyimino)propyl]-3-hydroxy-5-(2,4,6-trimethylphenyl)-cyclohex-2-enone) at 198 g a.i. ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa three to 5 d after the first metribuzin application. In both years, subsequent weed flushes were hand-weeded. Although the herbicide applications made in this study present a source of variability, there is no single, in-crop, broadleaf herbicide that is registered for use on all three grain legume species. It should be noted that previous studies found that post emergent applications of metribuzin had no negative effects on lupin, but in faba bean caused height reductions and some leaf burn which did not result in a significant seed yield reduction (Cole et al., 2005).

Total forage DM yields were measured when barley reached the silage stage (soft dough). This corresponded to 28 July 2004 and 4 Aug. 2005 at Barrhead, 3 Aug. 2004 and 2005 at Devon, and 9 Aug. 2004 and 26 July 2005 at Lacombe. The harvested sample was hand-cut at a height of 5 cm above the soil surface. In 2004, forage yield was sampled from two 0.4-m^2 quadrats, which had been marked after emergence. In 2005, forage yield was sampled by hand-cutting a 0.5-m strip from each plot resulting in a harvested area of 1.2 m^2. The harvested biomass was separated into legume and barley, dried at 40°C, and weighed to determine forage yield. Samples of each species were ground with a Wiley mill to 1 mm and then analyzed for forage nutritive value. Nitrogen was determined using a LECO N-analyzer (Model CN-2000, Leco Corp., St Joseph, MI) and multiplied by 6.25 for CP. The NDF, ADF, and ADL analyses were conducted using batch procedures outlined by ANKOM Technology Corporation (Fairport, NY) for an ANKOM200 Fiber Analyzer (Komarek, 1993; Komarek et al., 1994). Relative feed value (RFV) was calculated from ADF and NDF concentrations using the equations presented in Albrecht and Hall (1995).

Data Analysis

All data were tested for normality using PROC UNIVARIATE (SAS Institute, 2003). The analysis indicated that transformations were necessary for some data. Total yield, proportion of legume in the total yield, CP, and ADL were $\log_{10}(x+1)$ transformed while the protein yield was square root transformed ($x^{0.5}$). Acid detergent fiber and NDF data did not require transformation.

A preliminary analysis of variance indicated that forage DM yields were significantly different between site years ($P < 0.0001$) with yields at Devon 2004 = Barrhead 2004 > Barrhead 2005 = Devon 2005 > Lacombe 2005 > Lacombe 2004. Higher yields were associated with sites receiving higher rainfall and having higher spring soil moisture. Growing environment (site x year) was considered to be a random effect as sites were selected to represent the Parkland region of Alberta, Canada and climatic conditions throughout the study were typical for the area. Therefore, analyses of variance were performed using data combined across environments (site x year) with the MIXED procedure of SAS (Littell et al., 2006). Legume species and LPD were considered fixed effects. ADF and ADL data was analyzed with the NOBOUND option of PROC MIXED to get better control over Type I error and improve power as the Block x Legume(SiteYr) variance component was zero without this option (Littell et al., 2006).

Legume planting density effects (n=4) were separated with orthogonal polynomial contrasts, using coefficients derived in the IML procedure of SAS. Single degree of freedom contrasts were performed to detect significant differences in forage DM yield and forage nutritive value between the barley sole crop, and the three legume–barley intercrops. Comparisons were also made between the three legume–barley intercrops. A significance level of $P \leq 0.05$ was used for all statistical tests.

A simple economic analysis was conducted to determine the economic returns associated with intercropping legumes with barley for forage production based on the increased seeding costs and the resulting forage yield and nutritive value. Seed costs were obtained from a pedigreed-seed grower in the Barrhead area (R. Mueller, personal communication, Richard's Pedigreed Seed, Barrhead, AB, 2007). The cost of lupin seed was assumed to be equal to the price of faba bean seed. Feed grain prices at Barrhead in mid-February 2007 were used to determine forage values (L. Hein, personal communication, Champion Feed Services Ltd., Barrhead, AB, 2007). The silage pricing formula was obtained from Alberta Agriculture and Food (2004) to calculate the value of barley forage as:

$V = 8 \times B$

where V is the forage DM value (Canadian \$ 0.318 $\mathrm{Mg^{-1}}$) and B is the price of feed barley (Canadian \$ 21.8 $\mathrm{kg^{-1}}$). This formula was adapted to calculate the value of legume forage by substituting B with the price of feed pea or feed faba bean (Canadian \$ 27.2 $\mathrm{kg^{-1}}$), to account for the higher nutritive value of legume forage. The economic return was calculated as:

$N = (Y_L P_L + Y_b P_b) - (S_L R_L + S_b R_b)$

where N is the economic return (Canadian \$ $\mathrm{ha^{-1}}$), Y_L is the DM yield of the legume forage (Mg $\mathrm{ha^{-1}}$), P_L is the price of legume forage as determined by the silage pricing formula (Canadian \$ $\mathrm{t^{-1}}$), Y_b is the DM yield of the barley forage (Mg $\mathrm{ha^{-1}}$), P_b is the price of barley forage as determined by the silage pricing formula (Canadian \$ $\mathrm{t^{-1}}$), S_L is the cost of legume seed (Canadian \$ $\mathrm{kg^{-1}}$), R_L is the legume seeding rate (kg $\mathrm{ha^{-1}}$), S_b is the cost of barley seed (Canadian \$ $\mathrm{kg^{-1}}$), R_b is the barley seeding rate (kg $\mathrm{ha^{-1}}$). This equation was adapted from O'Donovan et al. (2001).

RESULTS AND DISCUSSION

Legume Species and Intercrop Effects

Forage Dry Matter Yields

Forage DM yields of the barley sole crop and pea–barley intercrops were similar but 1.3 to 1.5 Mg ha^{-1} greater than faba bean–barley or lupin–barley intercrops (Table 2-2). Chapko et al. (1991) in Wisconsin and Aasen et al. (2004) in central Alberta, Canada, also found pea–cereal forage mixtures did not out yield cereal forage sole crops. Poor legume-cereal intercrop DM production has been attributed to the greater competitive nature of one species over the other (Caballero et al., 1995). On the other hand, many studies have reported a yield increase of forage legume–cereal intercrops relative to cereal sole crops (Berkenkamp and Meeres, 1987; Ghanbari-Bonjar and Lee, 2003; Carr et al., 2004). Successful intercrops occur when each species occupies and accesses resources from different ecological niches while minimizing competitive interactions (Anil et al., 1998). Higher Cutlass pea–Niobe barley forage DM yields compared with Snowbird faba bean–Niobe barley and Arabella lupin–Niobe barley indicated the greater compatibility of Cutlass pea and Niobe barley for intercropping (Tables 2-2 and 2-3). For example, Cutlass pea and Niobe barley may have different peak times for water and nutrient uptake or their leaf arrangements may allow for greater light utilization. In contrast, if a particular combination of species and or varieties occupy similar ecological niches, it is unlikely that forage intercrop yield advantages will be observed. More productive faba bean and lupin intercrops might be achieved with a less competitive cereal species or variety.

Proportion of Legume in Forage DM

There was a significant legume species by LPD interaction for the proportion of legume in the total forage DM (Table 2-3) but this was primarily attributed to lupin–barley intercrops containing significantly less legume than faba bean–barley or pea–barley intercrops (Tables 2-2 and 2-3). Poor lupin performance may be attributed to its short stature (52 cm) relative to faba bean (93 cm) or pea (86 cm) (data not shown), and slow early-season growth which may have given barley a competitive advantage. Carruthers et al. (2000) noted the unsuitability of lupin for intercropping as lupin yields in intercrops were reduced by 94 to 100% compared with sole crop lupin yields and attributed poor lupin yields to shading by intercropped corn (*Zea mays* L.).

CP Concentrations

All legume–barley intercrops had higher CP concentrations relative to the sole barley crop (Table 2-2). Averaged across all legume-barley intercrops, intercrops had a 62% higher CP concentration compared to sole barley. This can be attributed to inheritantly higher CP concentrations of the legumes and higher

CP concentrations of the barley in the intercrop compared to the sole crop. Sole crop barley had a CP concentration of only 79 g kg^{-1} (Table 2-2) but the barley component of the faba bean, lupin, and pea intercrops had a 108, 92, and 100 g kg^{-1} CP concentration (data not shown), respectively. The increased CP concentration of intercropped barley has been attributed to N sparing by the legume resulting in high soil N levels for the non-legume (Vest, 1971), increased light, water, and nutrient uptake (Willey, 1979b), and possibly the transfer of fixed N from the legume to the non-legume (Eaglesham et al., 1981; Vasilas and Ham, 1985).

The CP concentration differed among intercrops (Tables 2-2 and 2-3). Faba bean–barley intercrops had the highest CP concentration (145 g kg^{-1}), followed by pea–barley (127 g kg^{-1}), and then lupin–barley (112 g kg^{-1}) intercrops. Ghanbari-Bonjar and Lee (2003) reported a CP concentration of 110 g kg^{-1} for a faba bean–wheat (*Triticum aestivum* L.) intercrop planted and harvested under similar conditions as our study. The reported CP of pea–barley forage intercrops range from 122 g kg^{-1} (Mustafa and Seguin, 2004) to 147 g kg^{-1} (Carr et al., 2004). Azo et al. (2006) reported CP concentrations of 101, 143, and 186 g kg^{-1} for lupin–triticale, lupin–wheat, and lupin–millet [*Pennesitum americanum* (L.) Leeke] forage intercrops, respectively. Forage nutritive value can be expected to vary depending on cultivar, agronomic practices, environmental conditions during growth (Juskiw et al., 2000), and the proportion of legume in intercrop mixtures, making direct comparisons between studies difficult.

Nutritive Value

Forage nutritive value, as indicated by the RFV, was improved in all legume–barley intercrops relative to the sole barley crop (Table 2-2). The lower barley sole crop RFV was attributed to the higher NDF and ADF concentrations in the sole crop barley compared to the legume–barley intercrops. Other authors have also reported higher NDF concentrations in sole crop barley relative to pea–barley intercrops (Chapko et al., 1991; Carr et al., 2004; Aasen et al., 2004). Of the legume–barley intercrops, pea–barley intercrops had the highest RFV (151), followed by faba bean–barley intercrops (143), while lupin–barley intercrops had the lowest RFV (132). Differences in RFV between legume species were attributed to differences in NDF, as ADF was similar between legume species. In central Alberta, Canada, Jedel and Helm (1993) also found no differences between the ADF concentration of faba bean–cereal and pea–cereal intercrops.

In agreement with Waldo and Jorgensen (1981), we found the ADL concentrations of faba bean–barley and pea–barley intercrops were greater than the ADL concentration of sole crop barley (Table 2-2). This can be attributed to higher lignin concentration of legumes compared to cereals (Waldo and Jorgensen, 1981). Although legume–barley forage contains more lignin than sole barley, Van Soest (1964) reported that alfalfa (*Medicago sativa* L.) had a higher lignin concentration than grasses, but they had equal digestibility. These findings warrant further investigation of the fiber digestibility of these legume-barley intercrops. The higher ADL concentration of faba bean–barley and pea–

barley intercrops compared to lupin–barley intercrops (Tables 2-2 and 2-3) was due to proportionately more legume in the faba bean and pea intercrops than the lupin intercrops.

Protein Yield

One of the main advantages of legume–cereal forage intercrops has been increased protein yield, relative to cereal sole crops (Walton, 1975; Berkenkamp and Meeres, 1987; Izaurralde et al., 1990; Aasen et al., 2004; Carr et al., 2004). There was a significant legume species by LPD interaction for protein yield (Table 2-3), but this was attributed primarily to much lower lupin-barley protein yields (1.4 Mg ha^{-1}) compared to faba bean-barley (1.8 Mg ha^{-1}) and pea-barley intercrops (1.7 Mg ha^{-1}) (Table 2-2). We observed 48% higher protein yields for legume–barley intercrops, on average, compared to the barley sole crop (Table 2-2). This was attributed to legume-barley intercrops having 62% higher CP concentrations, on average, relative to sole barley crops.

The highest protein yields were achieved with faba bean–barley and pea–barley intercrops (Tables 2-2 and 2-3). Although pea–barley and faba bean–barley intercrops had similar protein yields, it was achieved with different strategies. Faba bean–barley intercrops produced high protein yields due to the high CP concentration of each component (faba bean 176 g kg^{-1}; intercropped barley 108 g kg^{-1}) (data not shown). Pea–barley intercrops produced high protein yields due to a high forage DM yield and a high proportion of legume in the forage DM. Carr et al. (1998) noted that increasing intercrop protein yield required a significant proportion of legume DM in the intercrop mixture.

Legume Planting Density Effects

All measured parameters were affected by LPD, with the exception of total forage DM yield and ADF (Table 2-3). Proportion of legume, CP, and ADL increased, following a quadratic trend, while protein yield increased following a cubic trend, as LPD increased. As LPD increased, NDF decreased following a linear trend.

There was a trend (*P* = 0.07) for greater forage DM yields at higher LPD, and a significant quadratic trend (*P* = 0.03) indicated maximum forage DM yields at the 1.5x LPD (Table 2-3). Mean forage DM yields, averaged over all species, were 12.3, 12.4, 12.7, and 12.5 Mg ha^{-1} for intercrops with LPDs of 0.5, 1.0, 1.5, and 2.0x, respectively. Lower forage DM yields at the 0.5x and 1.0x LPD indicated that there were too few plants to use all the available resources in the system. At the 1.5x LPD, maximum intercrop yields occurred and maximum resource consumption was thought to be occurring. Forage yield decreased at the 2.0x LPD indicating increased competition at higher total plant populations.

Averaged over all species, the proportion of legume in the forage DM was 39, 51, 59, and 63% for intercrops with LPDs of 0.5, 1.0, 1.5, and 2.0x, respectively. Doubling the LPD from 1.0 to 2.0x increased the proportion of legume in the forage DM by only 24%. In Alberta, Canada, Izaurralde et al. (1990) also found that doubling the pea planting density increased intercropped pea DM yields by only 46%, indicating that legume yield was not directly proportional to the LPD.

Many of the forage nutritive value responses to increasing LPD can be explained by the increased proportion of legume in the forage DM. Compared to barley, legume species had higher CP, lower NDF, and higher ADL (data not shown). Therefore, as the proportion of legume in the forage DM increased, CP increased, NDF decreased, and ADL increased resulting in improved forage nutritive value. The increased protein yield in response to increased LPD may also be attributed to the increasing proportion of high protein legume in the intercrop DM.

Carr et al. (1998) examined forage DM and N yield of pea–cereal intercrops in North Dakota. Different trends between our study and Carr et al. (1998) may be attributed to higher cereal planting densities (93, 185, and 278 kernels m^{-2}) used by Carr et al. (1998) compared to the target barley plant population of 53 plants m^{-2} used in our study. As a result, Carr et al. (1998) found the cereal component dominated the intercrop which may explain why they observed no increase in forage DM or N yield as the intercropped-pea seeding rate increased. However, Carr et al. (1998) still found that the CP concentration of cereal–pea forage increased as the pea seeding rate increased. They concluded that the CP concentration of cereal–pea forage increased as the proportion of sown pea seeds to sown cereal kernels increased but forage N yield was unaffected by intercropping as the cereal component contributes more to yield than the pea component.

Economic Analysis of Intercropping

The increased seeding costs associated with the legume component of legume–barley intercropping relative to sole barley cropping can only be justified if intercrop yields are similar to or greater than sole barley, and nutritive value is improved. Aasen et al. (2004) compared the economic suitability of sole barley cropping and pea–barley intercropping for forage production. Based on 1998 costs, they determined input costs to be \$140 ha^{-1} for barley sole crops and \$190 to \$202 ha^{-1} for pea–barley intercrops. They concluded that small improvements in the nutritive value of the pea–barley mixture was not enough to off-set the increased costs of mixed cropping relative to sole cropping. However, their study did not attempt to determine a dollar value for the higher nutritive value forage, or costs for supplementing lower nutritive value feed, which might have altered their conclusions.

In our study, mean economic returns were \$983, \$939, \$1188, and \$1009 ha^{-1} and mean seed costs were \$120, \$102, \$100, and \$30 ha^{-1} for faba bean–barley, lupin–barley, pea–barley, and sole barley crop forage, respectively (Table 2-4). The high economic returns for pea–barley relative to the other legume–barley mixtures can be attributed to lower pea seed costs and higher legume forage DM yields. Pea–barley forage was the only mixture to have better economic returns than a sole barley crop, which was primarily attributed to the higher feed value of the legume DM relative to barley DM. Legume planting density and the legume species x LPD interaction had no effect on economic returns.

It should be mentioned that in Alberta, Canada, barley grown for forage typically receives high rates of N fertilizer. At Lacombe, AB, Canada, Juskiw et al. (2000) applied 72 kg N ha^{-1} and reported barley forage DM yields of 10.1 to 16.5 Mg ha^{-1}. In our study, the barley sole crop did not receive N fertilizer but comparable forage DM yields were achieved (13.3 Mg ha^{-1}). Although N fertilizer has the potential to increase sole barley forage DM yield, in our growing environment, small forage yield increases may not offset high N fertilizer costs.

Operational costs (time, fuel, equipment) associated with N fertilizer applications in a barley sole crop are replaced by the operational costs associated with planting the legume in the legume-barley intercrop, so we did not include these factors in the economic analysis. Our cost analysis did not include N fertilizer and application costs for sole barley crops, legume inoculant costs, herbicide costs, yield and price fluctuations, climatic factors, or the value of alternative forages, but it appears that the increased forage yield and nutritive value of pea–barley intercrops may be economically beneficial. Economic returns from the intercrops could be further increased if the value of improved yield stability, enhanced nutrient use, and improved weed, insect, or disease control associated with intercropping, were factored into the analysis.

Potential of Legume–Barley Intercrops

The legume–barley intercrops tested in this study produced forage DM yields between 11.8 to 13.8 Mg ha^{-1} which were similar to, or greater than, annual legume–cereal forage DM yields reported in other studies conducted in central Alberta, Canada of 6.6 to 12.3 Mg ha^{-1} (Berkenkamp and Meeres, 1987), and 8 to 11 Mg ha^{-1} (Jedel and Helm, 1993). Yields were also comparable with sole barley crop forage yields (10.1 to 16.5 Mg ha^{-1}) in the northern Prairies (Juskiw et al., 2000). Forage yields of pea–barley intercrops were equivalent to barley sole crops and therefore do not present a yield disadvantage to producers.

The greatest advantage of legume–barley forage intercrops was improved nutritive value relative to barley sole crops. Based on RFV, legume–barley forage intercrops had similar nutritive value to alfalfa at pre-bloom or early-bloom stage, while barley forage sole crops had similar nutritive value to alfalfa at mid-bloom (Rohweder et al., 1978). These intercrops offer the opportunity to produce annual forage with comparable nutritive value to perennial alfalfa. Annual legume–barley intercrops also do not have establishment and persistence difficulties associated with perennial alfalfa. In the absence of N fertilizer, legume–barley forage intercrops produced high CP concentrations and protein yields. The increased value associated with improved nutritive value resulted in a greater economic return for the pea–barley forage compared to the barley sole crop forage.

In addition to comparable sole barley crop forage yields and superior nutritive value, legume–barley intercrops increased cropping system diversity and supported biological N fixation. Increased cropping system diversity can improve nutrient cycling, regulate local hydrological processes, reduce pest populations, and detoxify noxious chemicals (Altieri, 1995). Legume–barley forage intercrops, which fix atmospheric N to meet their N requirements, have the added advantage of eliminating N fertilizer from production costs and may provide N and non-N benefits to subsequent crops. However, more work is needed to better understand the N and non-N benefits of incorporating legume-cereal intercrops into rotations with sole crops.

SUMMARY AND CONCLUSIONS

Legume-barley forage intercrop yield, nutritive value, and economic returns were influenced by the grain legume species and, in some instances, the LPD. Snowbird faba bean–Niobe barley intercrops had the highest CP concentration and protein yield, however, DM yields were less than Cutlass pea–Niobe barley or sole Niobe barley treatments. Arabella lupin–Niobe barley intercrops were low yielding with lower RFV and CP concentrations compared to other grain legume–barley intercrops. The poor performance of lupin–barley intercrops was attributed to the relatively poor competitive ability of lupin as indicated by the low proportion of legume in the total DM yield. Cutlass pea was best suited to intercropping with Niobe barley as yields were comparable to sole barley crops, nutritive value was improved, and economic returns were highest. Further study is required to identify different cereal species and variety intercrop combinations that will optimize faba bean and lupin forage DM production and the nutritive value of lupin intercrops.

Increasing the LPD from 0.5 to 2.0x had no effect on forage DM production or economic returns, but CP concentration, ADL concentration, and proportion of legume in the forage DM increased, while NDF decreased. Unlike some previous studies, we were able to consistently achieve improved nutrient values by growing legume-cereal intercrops that were not heavily dominated by the cereal species. This can be attributed to the relatively low barley seeding rate (53 plants m^{-2}) used in this study. Further study is required to assess the feed value and ensiling potential of grain legume-barley intercrops.

Grain legume-barley forage intercrops are a viable option for producers in the Parkland region of Alberta, Canada, compared to barley sole crops. Their greatest attributes were high CP concentrations, protein yields, and RFVs. With comparable nutritive value to bud to early bloom alfalfa, annual grain legume–barley intercrops may be an alternative to perennial alfalfa.

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Table 2-1. Preseeding soil properties and soil nutrient analysis (0-30 cm) at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005.

		Soil properties and nutrient analysis					
Year	Location	pH	Organic matter	Nitrate N	P	K	Sulphate S
			g kg^{-1}	------------------------ mg kg^{-1} ------------------------			
2004	Barrhead	6.3–6.4	86–97	12–18	<5	192–219	5
	Devon	5.8	86–93	24–25	7–14	112–186	12–16
	Lacombe	7.2–7.7	78–91	8–14	14–30	71–88	>20
2005	Barrhead	6.3–6.7	54–114	6–17	<5–7	207–257	3–5
	Devon	6.0–6.2	62–94	9–14	<5–10	111–214	11–20+
	Lacombe	7.9–8.0	84–95	9–18	14–60+	56–143	18–20+

Table 2-2. Sole barley (seeded at 210 plants m^{-2}) and grain legume-barley intercrop total forage yield (dry matter [DM] basis), protein yield (on a DM basis), proportion of legume in the legume–barley intercrop total DM (% legume on a DM basis), crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), and relative feed value (RFV), averaged across all legume planting densities, grown in 2004 and 2005 at Barrhead, Devon, and Lacombe, AB, Canada.

	Forage yield		Proportion of legume	Forage nutritive value parameter				
Treatment	Total DM	Protein	DM basis	CP	NDF	ADF	ADL	RFV
	----- Mg ha^{-1} ----		%	---------- g kg^{-1} ----------				
Faba bean–barley intercrop mean (FI)	12.0	1.8	56	145	435	281	43	143
Lupin–barley intercrop mean (LI)	12.0	1.4	35	112	475	278	37	132
Pea–barley intercrop mean (PI)	13.5	1.7	68	127	418	269	41	151
Barley sole crop (BS)	13.3	1.1	0	79	552	295	35	111
		ANOVA						
Species (S) *F* test (n=4)	***	***	***	***	***	***	***	--
SE† species	0.1	0.1	0.1	0.4	9.7	5.4	0.1	--
		CONTRASTS						
FI vs. BS	**	***	***	***	***	**	***	--
LI vs. BS	***	*	***	***	***	**	NS‡	--
PI vs. BS	NS	***	***	***	***	***	***	--

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Standard error of the difference of two least-squares means. Standard errors have been backtransformed where necessary.

‡ NS, nonsignificant at the 0.05 probability level.

Table 2-3. Total forage yield (dry matter [DM] basis), protein yield (on a DM basis), proportion of legume in the legume–barley intercrop total DM (% legume on a DM basis), crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL), of legume–barley intercrops by legume planting density (LPD) when grown in 2004 and 2005 at Barrhead, Devon, and Lacombe, AB, Canada.

		Forage yield		Proportion of legume,	Forage nutritive value parameter			
Treatment	LPD	Total DM	Protein	DM basis	CP	NDF	ADF	ADL
		----- Mg ha^{-1} -----		%	------------ g kg^{-1} ------------			
Faba bean–barley intercrop (FI)	0.5x	12.0	1.6	39	130	473	287	39
	1.0x	11.8	1.8	55	152	431	277	46
	1.5x	12.2	1.8	61	145	430	283	43
	2.0x	11.9	1.8	68	151	407	276	44
Lupin–barley intercrop (LI)	0.5x	11.8	1.3	24	104	490	277	31
	1.0x	11.9	1.4	33	113	484	283	37
	1.5x	12.2	1.5	40	118	465	275	40
	2.0x	12.0	1.4	43	116	462	278	38
Pea–barley intercrop (PI)	0.5x	13.1	1.6	55	124	432	267	39
	1.0x	13.6	1.7	64	124	430	275	39
	1.5x	13.8	1.8	75	130	413	268	40
	2.0x	13.5	1.8	77	130	396	265	44
			ANOVA					
Species (S) *F* test (n=3)		*	NS†	***	***	***	NS	*
SE‡ species		0.1	0.1	0.1	0.1	8.8	7.2	0.1
LPD *F* test (n=4)		NS	***	***	***	***	NS	***
SE‡ density		0.1	0.1	0.1	0.1	6.1	3.7	0.1
S x LPD *F* test (n=12)		NS	***	*	NS	NS	NS	NS
			Orthogonal Polynomials					
LPD linear		NS	***	***	***	***	NS	***
LPD quadratic		*	NS	***	***	NS	NS	*
LPD cubic		NS	*	NS	NS	NS	NS	NS
			Contrasts					
FI vs. LI		NS	NS	***	***	**	NS	**
FI vs. PI		*	NS	NS	**	NS	NS	NS
LI vs. PI		*	NS	***	**	***	NS	*

*, **, *** Significant at the 0.05, 0.01, 0.001 probability levels, respectively.

† NS, nonsignificant at the 0.05 probability level.

‡ Standard error of the difference of two least-squares means. Standard errors have been backtransformed where necessary.

Table 2-4. Economic returns for forage from legume–barley intercrops seeded at different legume planting densities (LPD) with a low barley seeding rate (53 plants m^{-2}) and a barley sole crop, seeded at the full barley seeding rate (210 plants m^{-2}), based on mean dry matter (DM) yields produced in 2004 and 2005 at Barrhead, Devon, and Lacombe, AB, Canada.

Treatment	LPD	Legume seeding rate	Barley seeding rate	Total seed cost†	Legume DM yield	Barley DM yield	Total forage value ‡	Economic return
		------- kg ha^{-1} -------		$ ha^{-1}	---------- Mg ha^{-1} ----------		------------ $ ha^{-1} ------------	
Faba bean–barley intercrop (FI)	0.5x	122	29	53	4.7	7.3	1055	1003
	1.0x	244	29	98	6.5	5.3	1085	987
	1.5x	365	29	143	7.4	4.8	1139	997
	2.0x	487	29	188	8.1	3.8	1133	946
	mean	305	29	120	6.7	5.3	1103	983
Lupin–barley intercrop (LI)	0.5x	102	29	45	2.8	9.0	992	947
	1.0x	204	29	83	3.9	8.0	1028	945
	1.5x	307	29	121	4.9	7.3	1076	955
	2.0x	409	29	159	5.2	6.8	1068	909
	mean	256	29	102	4.2	7.8	1041	939
Pea–barley intercrop (PI)	0.5x	105	29	44	7.2	5.9	1204	1160
	1.0x	211	29	81	8.7	4.9	1281	1200
	1.5x	316	29	118	10.4	3.5	1347	1229
	2.0x	422	29	155	10.4	3.1	1316	1161
	mean	264	29	100	9.2	4.4	1287	1188
Barley sole crop (BS)	0.0x	0	115	30	0.0	13.3	1039	1009
				<u>ANOVA</u>				
Species (S) *F* Test (n=4)				-	-	-	-	***
LPD *F* test (n=4)				-	-	-	-	NS§
S x LPD *F* test (n=13)				-	-	-	-	NS
				<u>Contrasts</u>				
FI vs. BS				-	-	-	-	NS
LI vs. BS				-	-	-	-	NS
PI vs. BS				-	-	-	-	*

*, **, *** Significant at the 0.05, 0.01, 0.001 probability levels, respectively.

† Total seed costs are based on \$0.35 kg^{-1} for certified pea seed, \$0.37 kg^{-1} for certified faba bean and lupin seed, \$0.26 kg^{-1} for certified barley seed.

‡ Total forage values are based on the silage pricing formula where the price for feed barley is \$142.38 Mg^{-1}, and the price of feed faba bean, lupin, and pea is \$150.65 Mg^{-1}.

§NS, nonsignificant at the 0.05 probability level.

Chapter 3

Weed interference, pulse species, and plant density effects on rotational benefits

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Chapter 3

Weed interference, pulse species, and plant density effects on rotational benefits

The rotational benefits of pulse crops have been well documented. Cereal yields have increased by 10 to 353% when grown on pulse stubble as compared with nonlegume stubble (Peoples and Herridge 1990) whereas protein concentrations have increased by 0.6 percentage units (Wright 1990a). The increased yield and protein concentration of cereals grown on pulse stubble are commonly attributed to improved N availability for the subsequent crop. Peoples et al. (1995) reported soil nitrate-N levels following legumes were 14 to 77 kg N ha^{-1} greater than levels following nonlegume crops. The increased N availability has been attributed to (1) N sparing by the pulse crop as pulse N demands are met by biological N fixation (Chalk 1998; Hardarson and Atkins 2003); (2) N mineralized from senesced legume leaves, roots, or nodules (Peoples et al. 1995); and (3) rhizodeposition of biologically fixed N products from nodulated roots (Sawatsky and Soper 1991).

Since improved subsequent crop yield and quality following pulse crops have been attributed to increased symbiotic N fixation, pulse crop management practices that improve symbiotic N fixation would be expected to increase subsequent crop yields. Keatinge et al. (1988) reported that weed removal increased the amount of N fixed by several legume species and improved protein yields of a subsequent hay crop. Faba bean intercropping studies have demonstrated that the proportion of N derived from fixation (%Ndfa) was significantly greater in intercropped faba bean compared with sole-crop faba bean despite there being a slight reduction in the total amount of N fixed (Danso et al. 1987). Soon et al. (2004) found that late weed removal, with herbicides, increased %Ndfa in a pea crop, but it did not affect total N fixation or subsequent crop yield. Geijersstam and Mårtensson (2006) found that intercropping pea with oat (*Avena sativa* L.) for forage increased %Ndfa and reduced the risk of nitrate leaching compared with pure pea stands, but subsequent crop yields were not affected. Although many studies have examined the effects of plant competition or intercropping on symbiotic N fixation, few studies have investigated the effects of pulse-crop weed competition on subsequent crop performance. We are not aware of any studies that investigated the effects of continuous weed competition in a pulse crop, harvested for grain, which also examined subsequent crop performance.

Altering planting densities to optimize crop yield has been well studied; however, the effects of altering planting densities to optimize N fixation has received little attention. In *Medicago* spp., planting density did not influence %Ndfa; however, the total amount of N fixed was greatly increased through the indirect effect of higher seeding rates increasing dry matter and total N yields (Materon and Danso 1991). In faba bean, increasing the cropping intensity index of sole-crop faba bean from 100 to 500 (17 to 83 plants m^{-2}) increased %Ndfa from 65 to 80% (Danso et al. 1987). In soybean [*Glycine max* (L.) Merr.], N fixation per gram nodule was higher at high planting densities than at low planting densities, but this was compensated for by greater nodule numbers and mass at the low planting density (Kapustka and Wilson 1990). On a unit-area basis, soybean N influx increased geometrically as planting density increased. The few studies that have examined the effects of planting density on %Ndfa and N-fixation yields present conflicting trends and reveal the need for further study in this area.

The aim of this study was to determine whether different pulse crop management practices can affect the productivity of a subsequent wheat crop. The specific objectives were to determine (1) the effects of pulse planting density (PPD) and weed interference on pulse seed yield, N-fixation yield, and %Ndfa; and (2) which pulse species and management practices resulted in the best subsequent wheat crop yield and grain protein concentration.

Materials and Methods

Site Description. Six, 2-yr field experiments were conducted between 2004 and 2006, at three sites in the Parkland region of central Alberta, Canada. At each site, the experiment was repeated twice. The first site, was located on a commercial farm near Barrhead, AB, Canada (54°6' N; 114°17' W), and was classified as an Orthic humic Gleysol (mesic Typic Endoaquoll) with a heavy clay texture. Rainfall and temperature data were collected from an Environment Canada weather station located 11.4 km from the test site at 54°5' N; 114°21' W. The second site was on a commercial farm near Devon, AB, Canada (53°26' N; 113°41' W). Soil at this site was classified as an Orthic black Chernozem (Typic Cryoboroll) with a silty clay-loam texture. An Environment Canada weather station (53°19' N; 113°34' W), located 9.1 km from the test site, was used to monitor rainfall and temperature data. The third site was at the Agriculture and Agri-Food Canada Research Centre in Lacombe, AB, Canada (52°27' N; 113°44' W), on a thin Orthic black Chernozem (frigid Typic Haplustoll) with a clay-loam texture. At this location, an on-site weather station was used to collect rainfall and temperature data. Pulses were grown with different management practices in year 1 (2004, 2005) and spring wheat was grown on all plots in year 2 (2005, 2006). Soil characteristics and soil nutrient analysis prior to seeding the pulse crop are presented in Table 3-1.

Year 1 – Pulse Crop Plot Management. The experimental design was a strip-split-plot randomized complete-block design with four blocks. Presence and absence of grassy weed interference was the strip plot. Pulse species was the main plot and PPD the subplot. Grassy weed interference of 37 plants m^{-2} was created by overseeding 'Niobe' barley. The three pulse species were 'Snowbird' tannin-free faba bean, 'Arabella' narrowleaf lupin, and 'Cutlass' field pea. Target pulse planting densities represented 0.5, 1.0, 1.5, and 2.0 times the recommended monoculture plant population for each pulse species in the

Parkland region of Alberta, Canada. Recommended populations for faba bean, lupin, and pea are 45, 100, and 75 plants m^{-2}, respectively (Alberta Agriculture and Food 2001) (Appendix 1-7). A barley plot was seeded to meet the recommended target plant population of 210 plants m^{-2}. Barley served as a nonfixing reference crop to determine N fixation and has been commonly used as the nonfixing system in calculating pea, faba bean, and lupin N fixation (Armstrong et al. 1997; Khan et al. 2003; Soon and Arshad 2004). Mean faba bean emergence was 98% of expected (range 77 to 123%), mean lupin emergence was 76% of expected (range 36 to 132%), and mean pea emergence was 97% of expected (range 82 to 117%). This resulted in pea and faba bean crops having plant populations very close to the targets. The lower lupin emergence resulted in planting densities that represented approximately 0.4, 0.8, 1.1, and 1.5 times the recommended monoculture plant population.

Some of the most common weeds in central Alberta, Canada, pea fields, common chickweed [*Stellaria media* (L.) Vill.], field pennycress (*Thlaspi arvense* L.), and shepherd's purse [*Capsella bursa-pastoris* (L.) Medik.] (Harker 2001), have a great deal of inherent variation in their competitive abilities, emergence periodicity, and functional traits (Lutman et al. 2000; Bullied et al. 2003; Iannetta et al. 2007). Because of the range of competitive abilities and unpredictability of natural weed populations, barley was selected as a model weed for this study which would provide standardized weed competition. Although barley is a model weed in this study, volunteer barley is also a common weed in Alberta, Canada, pea crops. Barley and six common weed species were found to have similar levels of N and P uptake (Andreasen et al. 2006). Although the model weed may not exactly mimic the resource acquisition of natural weed populations, the competitiveness of natural weed populations is very difficult to recreate given that competitive interactions vary depending on the infinite combination of seeding practices, weed and crop emergence dynamics, and climatic and edaphic conditions that are experienced in various weed–crop communities (Harker et al. 2007).

A model weed density of 37 plants m^{-2} was selected to represent typical grassy weed densities in field pea crops in western Canada. In central Alberta, Canada, a survey of commercial pea fields found mean volunteer barley populations of 35 plants m^{-2} (Harker 2001). In Saskatchewan, Canada, natural grassy weed populations in semileafless field pea ranged from 15 to 87 plants m^{-2} depending on the location and year (May et al. 2003).

Pulse crops were seeded within the first 2 weeks of May in 2004 and 2005. Individual subplots were 2.4 by 6 m. Pulse species were seeded in 12 rows with a small-plot hoe drill at 20-cm row spacing. For each pulse species, peat-based granular inoculant[1], containing the appropriate *Rhizobium* bacteria, was placed in the furrow. All pulses were seeded at the same seeding depth, with actual depths varying between 5 to 7.5 cm depending on soil moisture conditions. Immediately after seeding the pulse, barley was overseeded to create the weedy plots, with a 3.05-m hoe drill[2], at a depth of approximately 3.5 cm and a row spacing of 17.5 cm.

P (triple superphosphate), K (potassium chloride), and S (elemental sulfur) were applied to all treatments in the spring based on soil-test recommendations for a 4.6 Mg seed ha^{-1} pea grain crop. To avoid negative effects of fertilizer applications on seedling emergence, up to 118 kg ha^{-1} fertilizer was side-banded 2.5 cm from the seed row. If fertilizer recommendations exceeded this, the remaining fertilizer was broadcast and incorporated with harrows.

Prior to seeding, triallate at 1.7 kg ai ha^{-1} was applied and appropriately incorporated to control wild oat (*Avena fatua* L.) in all site–years, with the exception of Lacombe in 2004, where glyphosate at 440 g ai ha^{-1} was applied to control emerged weeds. To control heavy weed interference at Devon in 2004, glyphosate at 440 g ai ha^{-1} and MCPA at 300 g ai ha^{-1} were applied before crop emergence. After crop emergence in 2004, broadleaf weeds in the weedy and nonweedy faba bean, pea, and monoculture barley treatments were controlled with an initial application of bentazon at 1.1 kg ai ha^{-1} in 240 L ha^{-1} of water at 275 kPa when the pulses were at the three- to four- node stage. At Lacombe in 2004, metribuzin was applied at 203 g ai ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa, 2 wk after bentazon, on all treatments. In 2005 at Barrhead and Devon, broadleaf weeds were controlled with two applications of metribuzin at 138 g ai ha^{-1} using a water volume of 240 L ha^{-1} at 275 kPa, 10 d apart. At Lacombe in 2005 only one metribuzin application was made. At all sites wild oats were controlled with an application of tralkoxydim at 200 g ai ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa. 3 to 5 d after the first metribuzin application. In both years, subsequent weed flushes were hand-weeded.

Straw yields were measured, before crop desiccation, when each pulse species reached physiological maturity. A 0.4-m^2 quadrat was hand-cut, at a height of 5 cm above the soil surface. The harvested biomass from weedy treatments was separated into pulse and barley. Pulse pods and barley heads were removed from the plants to simulate grain harvest. The remaining crop residues were dried at 40 C and weighed to determine straw yield. After straw samples were collected, diquat at 360 g ai ha^{-1} in 240 L ha^{-1} of water at 275 kPa was applied. A nonionic surfactant[3] was added at 0.1% (v/v). Once desiccated, plots were combine-harvested. The harvested seed was dried at 40 C and weighed to determine pulse yields and weed (barley) seed biomass. To avoid straw mixing, between adjacent plots over winter, all straw residues were collected directly from the combine and removed from the field. This simulated straw baling. As a result, any fixed N available to the subsequent wheat crop arose from decomposing pulse crop root material, decomposing stubble (plant material remaining below the 5 cm cutting height of the combine), and pulse rhizodeposits.

Year 2 – Wheat Crop Plot Management. In the second year of the experiment, 'AC Intrepid' wheat was seeded on all plots at a target plant population of 250 plants m^{-2}, in the first week of May. No N was applied, but P, K, and S were applied with the seed in the furrow. Fertilizer rates were based on soil test recommendations. Weeds were controlled with thifensulfuron at 9.9 g ai ha^{-1}, tribenuron at 4.9 g ai ha^{-1}, quinclorac at 50 g ai ha^{-1}, and fenoxaprop at 70 g ai

ha^{-1} with a water volume of 120 L ha^{-1} at 275 kPa. Plots were combine-harvested on September 8, 2005 and August 22, 2006 at Barrhead, AB, Canada; September 2, 2005 and August 21, 2006 at Devon, AB, Canada; and August 29, 2005 and August 25, 2006 at Lacombe, AB, Canada. The harvested seed was dried at 40 C and weighed to determine yields.

Nitrogen Analysis and Nitrogen Fixation Estimates. Dried pulse and wheat, straw and seed samples, were ground to 1 mm and then analyzed for N concentration.[4] Seed N yield was determined by multiplying seed N concentration by seed yield. Similarly, straw N yield was calculated by multiplying straw N concentration by straw yield. Seed N concentration was multiplied by 5.7 for wheat and by 6.25 for pulse crops to determine seed protein concentrations (Engel et al. 1999; Miller et al. 2003). Wheat seed protein concentrations were corrected to 10% moisture so comparisons could be made with Engel et al. (1999). Symbiotic N fixation was determined by the total-plant N difference method based on the following formula (Rennie 1984):

$$N_{\text{fixed}}\ (\text{kg ha}^{-1}) = \text{N yield}_{\text{pulse}}\ (\text{kg ha}^{-1}) - \text{N yield}_{\text{reference crop}}\ (\text{kg ha}^{-1})$$

Data Analysis. All data were tested for normality using PROC UNIVARIATE.[5] The analysis indicated that square-root transformations $[(x+0.5)^{0.5}]$ were necessary for most data, with the exception of N-fixation yield data, to improve normality.

A preliminary ANOVA was performed to detect significant site–year by treatment differences using PROC MIXED,[5] where site–year was considered a fixed effect. For most dependent variables, there were significant site–year by treatment interactions ($P<0.05$). There were no significant site–year by treatment interactions for wheat seed protein concentration; therefore, an ANOVA was performed on that data combined across site–years, with site–year being considered a random effect. Subsequent ANOVA were performed on all other data from individual site–years, with the MIXED procedure of SAS (Littell et al. 2006). Weed interference, pulse species, and PPD were considered fixed effects. Data were analyzed with the NOBOUND option of PROC MIXED to get better control over Type I error and improve power when covariance parameter estimates of zero occurred in preliminary analyses (Littell et al. 2006). Data configurations in the figures reflect the statistical significance of main effects and interactions in the ANOVA. A significance level of $P \leq 0.05$ was used for all statistical tests.

Results and Discussion

In 2004, mean temperatures from May 1 to August 31 ranged from 12.6 to 12.8 C, depending on the site, and were cooler than the 30-yr average which ranged from 13.7 to 14.0 C. In 2005, growing season mean temperatures were slightly cooler than the 30-yr average and ranged from 12.8 to 13.5 C, depending on the site. All locations were warmer than the 30-yr average in 2006 with mean growing season temperatures ranging from 14.7 to 15.6 C. Overall, the pulse-years were conducted under cooler conditions than the 30-yr average while one wheat-year was conducted under slightly cooler conditions than 30-yr average and the other wheat year was conducted under warmer conditions than 30-yr average.

At Barrhead, AB, Canada, rainfall for May 1 to August 31 was less than the 30-yr average of 300 mm in 2004 (276 mm), 2005 (255 mm), and 2006 (206 mm). At Devon, AB,Canada, rainfall for May 1 to August 31 was similar to the 30-yr average (292 mm) in 2004 (301 mm) but less in 2005 (263 mm) and 2006 (232 mm). Rainfall for May 1 to August 31, at Lacombe, AB, Canada, was less than the 30-yr average (299 mm) in 2004 (249 mm) and 2005 (247 mm) but similar in 2006 (290 mm). In general, this study was conducted under conditions that were drier than the 30-yr average.

Mean pulse yield was highest at Barrhead and Devon in 2005 with 4,570 and 4,440 kg ha^{-1}, respectively (Figure 3-1). At Barrhead in 2004, Devon in 2004, and Lacombe in 2005, moderate pulse yields were achieved with 3,640, 3,420, and 3,190 kg ha^{-1}, respectively. The lowest pulse yield was recorded at Lacombe in 2004 (2,590 kg ha^{-1}). Wheat seed yield ranged from 3,310 to 5,490 kg ha^{-1} and were in the order of (greatest to least) Barrhead 2005 > Barrhead 2006 = Devon 2006 > Devon 2005 ≥ Lacombe 2006 = Lacombe 2005 (Table 3-2).

Year 1 – Weed Biomass and Pulse Crop Performance. A considerable number of studies have reported that increased crop density results in increased weed suppression (Mohler 1996). In this study, weed biomass in faba bean decreased from 6,280 to 2,950 kg ha^{-1}, representing a 53% reduction in weed biomass as PPD increased from 0.5 to 2.0 times (data not shown). Similarly, increasing the pea PPD from 0.5 to 2.0 times resulted in the weed biomass being reduced from 4,880 to 1,990 kg ha^{-1}, representing a 59% reduction in weed biomass. These trends indicate that some weed control can be achieved with cultural practices. Lemerle et al. (2006) also found that grassy weed dry weight was reduced with increasing pea density. Surprisingly, increasing the lupin PPD only reduced weed biomass from 7,390 to 6,600 kg ha^{-1}, representing an 11% reduction in weed biomass, indicating that higher than normal lupin planting densities were unable to greatly increase the competitive ability of lupin against weeds.

For each pulse species, seed yield was significantly higher in the absence of weed interference than in the presence of weed interference (Figure 3-1).

Mean pulse seed yield was 4,610 kg ha^{-1} and 2,680 kg ha^{-1} for pulses grown in the absence and presence of grassy weed interference, respectively.

In the absence of weed interference, faba bean produced higher seed yields than pea in three site–years, faba bean and pea produced similar yields in one site–year, and faba bean produced lower yields than pea in two site–years (Figure 3-1). Higher faba bean yields were produced in growing environments with annual precipitation ranging from 466 to 563 mm, indicating their high moisture requirements. In growing environments with lower annual precipitation (346 to 366 mm), pea produced the highest yield. In this study, maximum faba bean and pea seed yield was 7,640 kg ha^{-1} and 6,460 kg ha^{-1}, respectively. However, over the course of the study, faba bean yields were more variable than pea yields. This may be partially attributed to faba bean being sensitive to heat and drought stress during flowering and the absence of locally adapted cultivars. Lupin produced consistently low seed yields in the absence of weed interference (2,370 to 4,020 kg ha^{-1}) which may be partially attributed to less agronomic experience with the crop and the absence of locally adapted cultivars.

In the presence of weed interference, pea produced higher yields than faba bean in three site–years, pea and faba bean produced similar yields in two site–years, and pea produced lower yields than faba bean in one site–year (Figure 3-1). Mean yield reduction was 42 and 27% for faba bean and pea grown in the presence of weed interference compared with faba bean and pea grown in the absence of weed interference, respectively. Overall, faba bean was less competitive than pea and achieving high faba bean yields required effective weed control. Knudsen et al. (2004) found that in a faba bean-barley mixture faba bean comprised 63% of the grain yield, while pea comprised 78% of the grain yield in a pea-barley mixture, indicating the increased competitiveness of pea relative to faba bean. In our study, lupin yields were reduced by an average of 67% in the presence of grassy weeds compared to lupin yields in the absence of weed interference. The poor competitive ability of lupin was also demonstrated by Knudsen et al. (2004) with lupin comprising only 44% of a lupin-barley mixture on a sandy loam soil. Compared to faba bean and pea, lupin had a lower yield potential and was less competitive. For lupin to be a practical option for producers, lupin seed must have a higher market value than pea or faba bean to compensate for lower yields and higher input costs for weed control.

There was a significant weed interference by PPD interaction for pulse seed yield in five of six site–years (Figure 3-2A) (Appendix 1-8). As PPD increased from 0.5 to 2.0 times, pulse seed yield (averaged over all pulse species and site–years) increased 59% (from 1,970 to 3,130 kg ha^{-1}) in the presence of weed interference but increased only 12% (from 4,250 to 4,770 kg ha^{-1}) in the absence of weed interference. Under weed-free conditions, maximum pulse seed yields were often achieved with the 1.0 times PPD. However, a high PPD (1.5 or 2.0 times) was necessary to achieve optimum seed yields in the presence of weed interference. Townley-Smith and Wright (1994) also reported field pea yield increased in the presence of weeds when the pea seeding rate was increased from 50 to 100 seeds m^{-2}.

In three growing environments, there was a significant pulse species by PPD interaction for pulse seed yield (Figure 3-2B) (Appendix 1-8). For lupin and pea, highest seed yields were generally achieved with either 1.0 or 1.5 times PPD, depending on the growing environment. For faba bean, highest yields were achieved with 1.5 times PPD in three growing environments and with 2.0 times PPD in two growing environments. L´opez-Bellido et al. (2005) reported that the optimum faba bean plant density may be greater than 60 plants m^{-2} for faba bean crops grown in temperate conditions. The cool temperate climate of our study area, required that the tannin-free faba bean planting density be increased from 45 (1.0 times PPD) to 68 plants m^{-2} (1.5 times PPD) to consistently achieve optimum yield.

Pulse crop performance can be optimized with proper management techniques. Seed yields increased by approximately 2,000 kg ha^{-1} when pulse crops were grown in the absence of grassy weed interference (Figure 3-2A). Lupin was the most sensitive to weed interference and experienced the greatest yield loss of the three species, making weed control in lupin crops crucial. In most environments, pea achieved optimum yields with 1.0 times PPD which corresponds to 75 plants m^{-2} (Figure 3-2B). For lupin, optimum yields were produced with the 1.5 times PPD. Taking into account the 76% lupin emergence, the 1.5 times PPD corresponds to 114 plants m^{-2}, which is similar to the initial target 1.0 times PPD of 100 plants m^{-2}. Faba bean required a PPD of 1.5 or 2.0 times (68 to 90 plants m^{-2}) to consistently achieve optimum yields.

Year 1 – Pulse Crop N Yields and %Ndfa. In the absence of weed interference, faba bean produced the highest N-fixation yields, in four site–years, with N yields ranging from 70 to 223 kg N ha^{-1} (Figure 3-3A). Pea and lupin produced similar N-fixation yields. In the absence of weed interference, pea N-fixation yields ranged from 78 to 147 kg N ha^{-1} and lupin N-fixation yields ranged from 46 to 173 kg N ha^{-1}. Our results were similar to the findings of Sparrow et al. (1995), who reported field pea fixed between 65 to 123 kg N ha^{-1} and faba bean fixed between 82 to 228 kg N ha^{-1} as determined by the N-difference method using barley as a reference species. In addition, Sparrow et al. (1995) reported faba bean fixed more N than pea in three of four site–years. The amount of N fixed by lupin, in our study, was lower than values (95 to 283 kg N ha^{-1}) reported by Unkovich et al. (1995) and by Pálmason et al. (1992) (195 kg N ha^{-1}). Differences may be partially attributed to Unkovich et al. (1995) using the ^{15}N natural abundance method to measure N fixation and Pálmason et al. (1992) using the ^{15}N-isotopic dilution method to measure N fixation. However, lower lupin N-fixation yields, in our study, may have been partially attributed to poor lupin establishment.

Faba bean grown in the presence of weed interference produced lower N-fixation yields (mean 94 kg N ha^{-1}) than faba bean grown in the absence of weed interference (mean 155 kg N ha^{-1}) (Figure 3-3A). Similarly, Danso et al. (1987) found that mean faba bean N fixation was reduced from 79 to 71 kg N ha^{-1}, when faba bean was grown with barley. The same trend was observed for lupin, with a mean of 32 kg N ha^{-1} fixed in the presence of weed interference and a mean of

108 kg N ha^{-1} fixed in the absence of weed interference. Keatinge et al. (1988) also reported a reduction in N fixation from 23.1 to 21.8 kg N ha^{-1}, because of the presence of weed interference. Reduced N fixation in the presence of weed interference has been attributed to reduced legume dry matter rather than reduced %Ndfa (Danso et al. 1987). In this study, the relatively large reduction in N fixation, which is attributed to weed interference, may be attributed to increased competitiveness of the model weed.

Despite a consistent trend, N-fixation yields of pea grown in the presence (mean 90 kg N ha^{-1}) and absence of weed interference (mean 114 kg N ha^{-1}) were not significantly different in five of six site–years (Figure 3-3A). Similarly, Soon et al. (2004) reported that total N fixed by field pea was not affected by weed interference that was present for 4 wk after crop emergence.

In general, there was a significant linear or quadratic increase in N-fixation yields in response to increasing the PPD (Figure 3-3B). Mean N-fixation yields (averaged over all pulse species and site–years) were 82, 99, 105, and 111 kg N ha^{-1} for 0.5, 1.0, 1.5, and 2.0 times the PPD, respectively. Ayaz et al. (2004) reported similar trends with pea and lupin straw N yields typically increasing in response to increasing plant populations. At Devon and Lacombe, AB, Canada, in 2005, there was a significant pulse species by PPD interaction for N-fixation yield. This was caused by lupin showing no response to PPD at Devon, AB, Canada, in 2005, and faba bean showing no response to PPD at Lacombe, AB, Canada, in 2005.

The %Ndfa was significantly affected by pulse species at all site–years, except for Devon, AB, Canada, in 2005 (Figure 3-4A) (Appendix 1-8). Averaged over all site–years, %Ndfa was 54, 43, and 49% for faba bean, lupin, and pea, respectively, in the absence of weed competition. It should be noted that relatively low %Ndfa values for all crops may be attributed to the methodology used in this study because it does not account for the possibility of lower soil N uptake by the pulses relative to the barley reference (Senaratne and Hardarson 1988). At Devon, AB, Canada, in 2004, there was a significant weed interference by pulse species crossover interaction. This was caused by lupin, grown in the presence of weed interference, having a lower %Ndfa compared with lupin grown in the absence of weed interference. At Lacombe, AB, Canada, in 2005, there was a significant interaction for weed interference by pulse species, but it was one of magnitude. Although not significant at most site–years, %Ndfa tended to be higher in the presence of weed interference (mean 50%) than in the absence of weed interference (mean 47%). In intercropping studies, Danso et al. (1987) observed a higher %Ndfa for intercropped faba bean (92%) compared with sole-cropped faba bean (74%). Similarly, Soon et al. (2004) reported that pea subjected to weed competition for a longer time derived more N from symbiotic fixation. The same trend was observed for sole-crop and intercropped lupin (Pálmason et al. 1992). These trends were attributed to the nonfixing crop (i.e., weed) decreasing soil N, thereby forcing the legume to fulfill its N requirements by N fixation. In our study, it appears that the weed's demand for soil N did not significantly affect pulse %Ndfa.

Increasing the PPD from 0.5 to 2.0 times resulted in a significant linear increase of %Ndfa at Barrhead, AB, Canada, in 2005 and a significant linear increase of %Ndfa, for lupin, at Lacombe, AB, Canada, in 2004 (Figure 3-4B). Pulse planting density did not significantly affect %Ndfa in other site–years. Danso et al. (1987) reported that doubling the cropping intensity of sole-cropped faba bean increased %Ndfa by 20%. They attributed the %Ndfa increase to less soil N being available to each plant, which stimulated N fixation. In our study, we presumed that high rates of soil organic matter mineralization limited soil N deficits and resulted in few %Ndfa responses.

Just as pulse crop yield was optimized with proper management techniques, proper management techniques increased N-fixation yields. For faba bean and lupin, optimum N fixation was achieved in the absence of weed interference (mean nonweedy N-fixation yields of 155 and 108 kg N ha^{-1}, respectively) (Figure 3-3A). However, pea N-fixation yields (mean 103 kg N ha^{-1}) were not affected by weed interference. N-fixation yields were further increased, from 82 to 111 kg N ha^{-1}, by increasing the PPD from 0.5 to 2.0 times (Figure 3-3B). Fifty-nine percent of the N-fixation yield increase can be attributed to increasing the PPD from 0.5 to 1.0 times, with further increases in PPD resulting in proportionately smaller increases in N fixation. We saw little response of %Ndfa to management practices (Figure 3-4), but that may be attributed to the studies being conducted in an area where soils have relatively high levels of available N.

Year 2 – Subsequent Wheat Crop Performance. Wheat seed yields, averaged over all site–years, were 4,500, 4,120, and 4,610 kg ha^{-1}, for wheat grown on faba bean, lupin, and pea stubble, respectively (Table 3-2). Wheat yields on pea stubble were significantly greater than or equal to wheat yields on faba bean stubble in five site–years. Wheat yields on faba bean stubble were significantly greater than wheat yields on pea stubble in only one site–year. Wheat yields on lupin stubble were generally lower than on other stubble types. In agreement with our findings, higher yields on pea stubble, as compared with faba bean stubble, have been reported by some authors (Maidl et al. 1996) whereas similar yields on pea and faba bean stubble have also been reported (Senaratne and Hardarson 1988; Wright 1990b). Many studies have reported higher subsequent crop yields on lupin stubble compared with pea stubble (Evans et al. 1991; Armstrong et al. 1997; Jensen et al. 2004). Higher yields on lupin stubble have been attributed to greater root N yields (Jensen et al. 2004) and greater accumulation and N fixation by lupin (Armstrong et al. 1997). Differences between our study and previous studies can be attributed to poor lupin performance. Because lupin emergence was only 76% of expected, this likely resulted in less N fixation and reduced N and non-N contributions to the subsequent wheat crop.

The effect of weeds, in the previous pulse crop, on subsequent wheat yield was site specific (Table 3-2). Mean wheat yields were 4,580 and 4,240 kg ha^{-1} for wheat grown on nonweedy and weedy pulse stubble, respectively (data not shown). However, the difference was only significant in two site–years

(Barrhead and Devon 2006). Soon et al. (2004) also found that the time of weed removal in pea crops had no effect on the yield of a subsequent cereal crop.

Wheat seed yields increased significantly in response to increasing PPD in two site–years (Barrhead and Lacombe 2005) (Table 3-2). Averaged over all pulse species, mean wheat seed yields were 4,340, 4,110, 4,430, and 4,540 kg ha^{-1} for wheat grown on pulse stubble with 0.5, 1.0, 1.5, and 2.0 times the PPD, respectively (data not shown).

Wheat seed protein concentration was affected by the previous pulse species ($P < 0.01$), weed interference ($P < 0.05$), and PPD ($P < 0.05$). Wheat seed protein was higher when wheat was grown on nonweedy stubble (mean 122 mg g^{-1}) compared with weedy stubble (mean 119 mg g^{-1}) (Table 3-3). Pea and faba bean stubble produced higher wheat seed protein concentrations; each have a mean 122 mg g^{-1}, compared with lupin stubble (mean 118 mg g^{-1}). In agreement with this, Wright (1990a) reported that faba bean and pea stubble produced similar increases in the seed protein concentration of a subsequent barley crop. Increasing the PPD resulted in a small linear increase ($P < 0.05$) in the subsequent wheat crop protein concentration from 121 to 122 mg g^{-1} (data not shown); however, this trend was not biologically significant. The absence of a significant site–year by treatment interaction for wheat seed protein concentration indicated a consistent increase in protein concentration because of improved pulse crop management practices. Similarly, Zentner et al. (2001) reported wheat protein response was more consistent than wheat yield response in a wheat-lentil (*Lens culinaris* Medik.) rotation.

Grain protein concentration below the critical limit of 132 mg g^{-1} has been used as a reliable indicator of insufficient N under a range of moisture regimes and across various spring wheat genotypes (Engel et al. 1999). Although no N fertilizer was added in year 2, N sufficiency was achieved in two site–years, (Barrhead 2005 and Lacombe 2006) when mean grain protein concentrations were 135 and 132 mg g^{-1}, respectively (Table 3-3). At Barrhead, AB, Canada, in 2005, all previous pulse crops supplied sufficient N to produce optimal wheat yields. Therefore, wheat yield and protein differences between treatments may have been caused by a complex interaction of non-N factors including pulse crop effects on soil water (Gan et al. 2003); interruption of pest cycles (Derksen et al. 2002; Krupinsky et al. 2002); increased P, K, and S availability (Bullock 1992); and ameliorated soil structure (Bullock 1992; Karlen et al. 1994). At Lacombe, AB, Canada, in 2006, all nonweedy pulse stubble provided sufficient N to meet the wheat crop requirements, whereas the weedy lupin and pea stubble were N deficient. Barrhead 2006, Devon 2005, Devon 2006, and Lacombe 2005 were N deficient with mean grain protein concentrations of 131, 116, 112, and 99 mg g^{-1}, respectively. At Barrhead, AB, Canada, in 2006, it was more common for the weedy pulse stubble to be N deficient. However, in the other three N-deficient sites, all treatments were somewhat N deficient. Treatment differences at the N-deficient sites were likely the result of N availability and non-N factors, described above.

In 2006, the mean protein content of all grades of Canadian western red spring wheat grown in Alberta, Canada, adjusted to 13.5% moisture, was 13.1%

(Canadian Grain Commission 2007). By comparison, the mean protein content of wheat grown at our N-sufficient sites, adjusted to 13.5% moisture, was 12.9%. The comparable protein contents indicate that quality wheat crops can be grown on pulse stubble without additional N fertilizer, on soils high in organic matter, in some site–years.

Linking Pulse Management to Subsequent Wheat Crop Performance. Although weed presence greatly reduced pulse crop yields (mean 42% yield reduction) and N-fixation yields (mean 43% N-fixation yield reduction), the presence of weeds in the previous pulse crop reduced subsequent wheat crop yields by only 7%. Similarly, Soon et al. (2004) reported that early weed removal increased pea seed yield, but the yield of a subsequent barley crop was not affected by the timing of weed removal in the previous pea crop. Based on the findings of our study, and the findings of Soon et al. (2004), weed interference in the previous pulse crop caused small subsequent crop yield decreases, but only when weed interference was present for the entire growing season. In commercial cropping systems, weed interference would increase the weed seed bank, which could create significant weed problems in the subsequent crop that could contribute to substantial wheat yield reductions or increase the cost of weed control.

Increasing the PPD from 0.5 to 2.0 times increased pulse crop yield by an average of 27% and N-fixation yield by an average of 35%, whereas wheat crop yields increased by an average of only 5%. Once again, pulse crop management practices had a relatively small effect on the subsequent wheat crop yield.

Although many studies have focused on the notion of pulse crops increasing the N availability to subsequent crops, detailed studies have found that the N contribution of pulses to subsequent crops was smaller than expected (Stevenson and van Kessel 1996). For example, only 2 to 15% of ^{15}N originally present in pea or lentil crops was accumulated in subsequent cereal crops (Bremer and van Kessel 1992; Jensen 1994). This suggests why large increases in N fixation, which occur with improved management practices, do not translate into subsequent crop yield increases of equal magnitude. However, the long-term importance of fixed N to the cropping system must not be ignored. Campbell et al. (1992) found evidence documenting the importance of this in a long-term study where the N supplying power of the soil was enhanced in a wheat-lentil rotation compared with monoculture wheat rotations.

The primary factor affecting subsequent wheat crop yield was pulse species. Wheat grown on pea stubble produced 11% higher yields than lupin stubble but only 2% higher yields than faba bean stubble. Consistently high wheat seed yields were achieved on pea and faba bean stubble, despite pea having lower N-fixation yields compared with faba bean. High wheat yields on pea stubble may be attributed to synchronous N release from decomposing pea residues with subsequent crop N demands, and non-N rotational benefits (i.e., pulse crop effects on soil water (Gan et al. 2003), interruption of pest cycles (Derksen et al. 2002; Krupinsky et al. 2002), increased P, K, and S availability

(Bullock 1992), and ameliorated soil structure (Bullock 1992; Karlen et al. 1994)) of pea being greater than non-N rotational benefits of faba bean or lupin. Stevenson and van Kessel (1996) suggested that non-N rotational benefits may indirectly enhance N accumulation in a subsequent cereal crop. An assessment of non-N rotational benefits and N-release timing from decomposing pea, faba bean, and lupin residues should be investigated further.

In conclusion, we found that pulse seed yield, N-fixation yield, and subsequent crop yields differed greatly depending on the pulse species. Increasing the PPD and an absence of weed interference resulted in the highest pulse seed and N-fixation yields. However, management practices that greatly increased N-fixation yields resulted in disproportionately smaller subsequent wheat yield increases. Increasing the PPD from 0.5 to 2.0 times increased subsequent wheat crop yields by 5%, but that trend was not observed in all growing environments. Nonweedy pulse stubble was able to supply many subsequent wheat crops with sufficient N, and N deficiency was more common on weedy pulse stubble. Although not significant in all growing environments, wheat yields were an average of 7% higher on nonweedy pulse stubble compared with weedy pulse stubble.

Sources of Materials

[1] Soil Implant +, EMD Crop BioScience, 13100 West Lisbon Avenue Suite 600, Brookfield, WI 53005.

[2] 9450 John Deere Hoe Drill, Deere & Company World Headquarters, One John Deere Place, Moline, IL 61265.

[3] Agral 90, Syngenta Crop Protection Canada, Inc., 140 Research Lane, Research Park, Guelph, ON N1G 4Z3.

[4] LECO CN-2000, LECO Corporation, 3000 Lakeview Avenue, St. Joseph, MI 49085.

[5] SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.

[6] Bodycote Testing Group, 7217 Roper Road NW, Edmonton, AB T6B 3J4.

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Table 3-1. Year 1 preseeding soil properties and soil nutrient analysis (0 to 30 cm) at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005. Presented values are the results from separate tests run on a composite sample by an accredited testing laboratory.[6]

	2004			2005		
	Barrhead	Devon	Lacombe	Barrhead	Devon	Lacombe
pH	6.3–6.4	5.8	7.2–7.7	6.3–6.7	6.0–6.2	7.9–8.0
Organic matter, g kg^{-1}	86–97	86–93	78–91	54–114	62–94	84–95
Nitrate N, mg kg^{-1}	12–18	24–25	8–14	6–17	9–14	9–18
P, mg kg^{-1}	<5	7–14	14–30	<5–7	<5–10	14–60+
K, mg kg^{-1}	192–219	112–186	71–88	207–257	111–214	56–143
Sulphate S, mg kg^{-1}	5	12–16	>20	3–5	11–20+	18–20+

Table 3-2. Wheat seed yield, in year 2 of the cycle, grown on faba bean, lupin, or pea stubble, averaged over weed interference (W) and pulse planting densities (PPD) at Barrhead, Devon, and Lacombe, AB, Canada, in 2005 and 2006.

	Barrhead		Devon		Lacombe	
Stubble type	2005	2006	2005	2006	2005	2006
	----------	----------	---------- kg ha^{-1}	----------	----------	----------
Faba bean	5,190 b[a]	4,630 a	4,120 ab	5,280 a	3,710 b	4,090 a
Lupin	5,160 b	4,750 a	3,690 b	4,140 c	3,310 c	3,660 b
Pea	5,490 a	4,900 a	4,500 a	4,730 b	4,100 a	3,940 ab
ANOVA						
Weed (W) *F* test	NS	*	NS	*	NS	NS
SE[b] weed	1.4	0.6	0.1	0.1	1.9	0.8
Species (S) *F* test	*	NS	*	**	**	*
SE[b] species	0.1	0.5	3.3	1.6	0.4	0.5
W by S *F* test	*	NS	**	NS	NS	NS
PPD *F* test	**	NS	NS	NS	***	NS
SE[b] PPD	0.1	0.1	0.4	0.2	0.1	0.1
W by PPD *F* test	NS	**	NS	*	NS	NS
S by PPD *F* test	NS	NS	NS	***	NS	*
W by S by PPD *F* test	NS	NS	NS	NS	NS	NS

[a] Means within a column that are followed by the same letter were not significantly different by Fisher's Protected LSD test ($P < 0.05$).

[b] Standard error of the difference of two least-squares means. Standard errors have been back-transformed where necessary.

*, **, ***, and NS indicate significance at $P < 0.05$, $P < 0.01$, $P < 0.001$, and not significant, respectively.

Table 3-3. Wheat seed protein concentration adjusted to 10% moisture content, in year 2 of the cycle, grown on nonweedy (NW) or weedy (W), faba bean, lupin, or pea stubble, averaged over pulse planting densities (PPD) at Barrhead, Devon, and Lacombe, AB, Canada, in 2005 and 2006.

	2005			2006		
Stubble type	Barrhead	Devon	Lacombe	Barrhead	Devon	Lacombe
	---------- mg g^{-1} ----------					
NW faba bean	134	117[a]	98[a]	133	119[a]	134
NW lupin	135	120[a]	95[a]	128[a]	105[a]	136
NW pea	140	119[a]	99[a]	137	120[a]	132
NW mean	136	118[a]	97[a]	133	114[a]	134
W faba bean	135	117[a]	108[a]	129[a]	107[a]	133
W lupin	133	111[a]	96[a]	120[a]	105[a]	130[a]
W pea	134	114[a]	100[a]	135	114[a]	126[a]
W mean	134	114[a]	101[a]	128[a]	108[a]	129[a]
Overall mean	135	116[a]	99[a]	131[a]	112[a]	132

[a] Denotes treatments where the grain protein concentration was below the critical limit of 132 mg g^{-1}, indicating low N sufficiency.

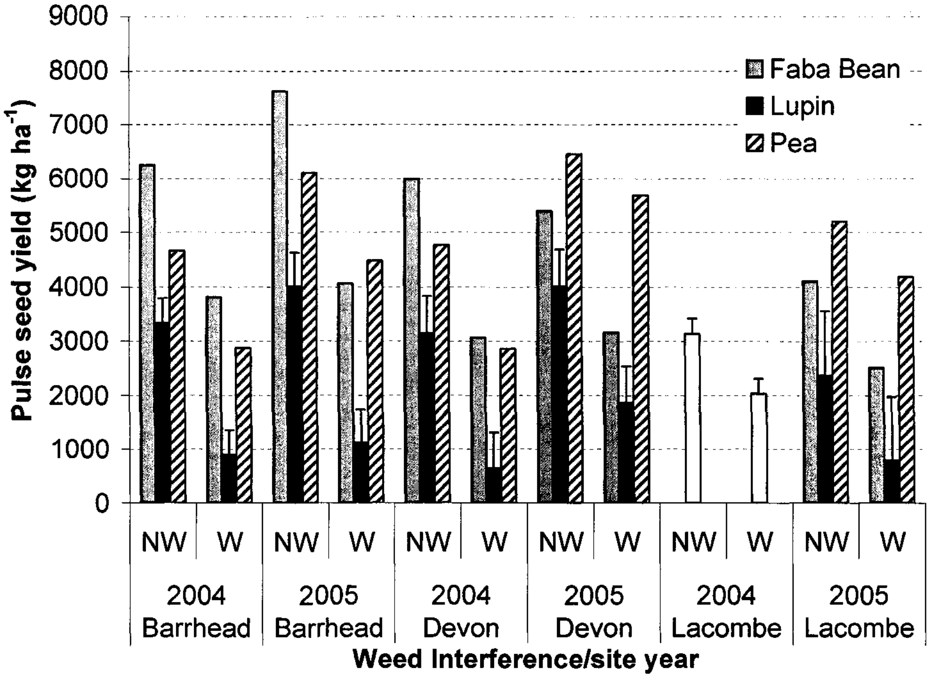

Figure 3-1. Faba bean, lupin, and pea seed yield after growth in the presence (W) and absence (NW) of weed interference at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005. The graph indicates the weed by pulse species interaction when the interactions are significant in the ANOVA. When these interactions are not significant, weed interference (significant at all site–years) is shown as white bars. $LSD_{0.05}$ bars are different for each site–year, and apply to all pulse species.

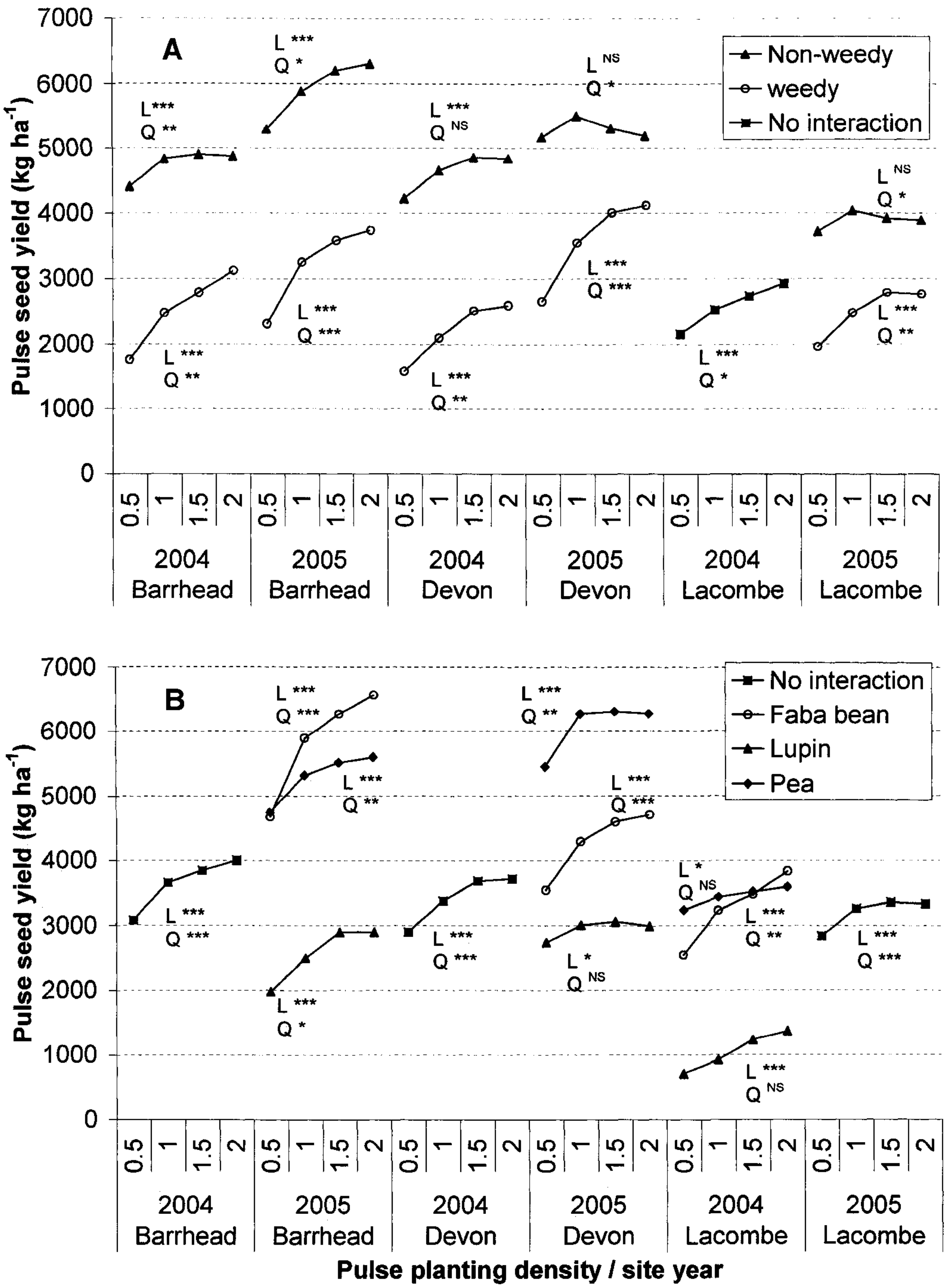

Figure 3-2. Pulse seed yield for PPD of 0.5, 1.0, 1.5, and 2.0 times the recommended rate for each pulse species (faba bean, lupin, pea) or weed interference (nonweedy, weedy) at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005. (A) The top graph indicates the weed interference by PPD interaction and (B) the bottom graph indicates the pulse species by PPD interaction when the interactions are significant in the ANOVA. When these interactions are not significant, PPD (significant at all site–years) is shown as black squares (■). Weed interference is indicated by solid triangles (▲, nonweedy), or open circles (○, weedy). Pulse species are indicated by open circles (○, faba bean), solid triangles (▲, lupin), or solid diamonds (♦, pea). Abbreviations: L, significance of a linear trend; PPD, pulse planting density; Q, significance of a quadratic trend. *, **, ***, and NS indicate significance at $P < 0.05$, $P < 0.01$, $P < 0.001$, and not significant, respectively.

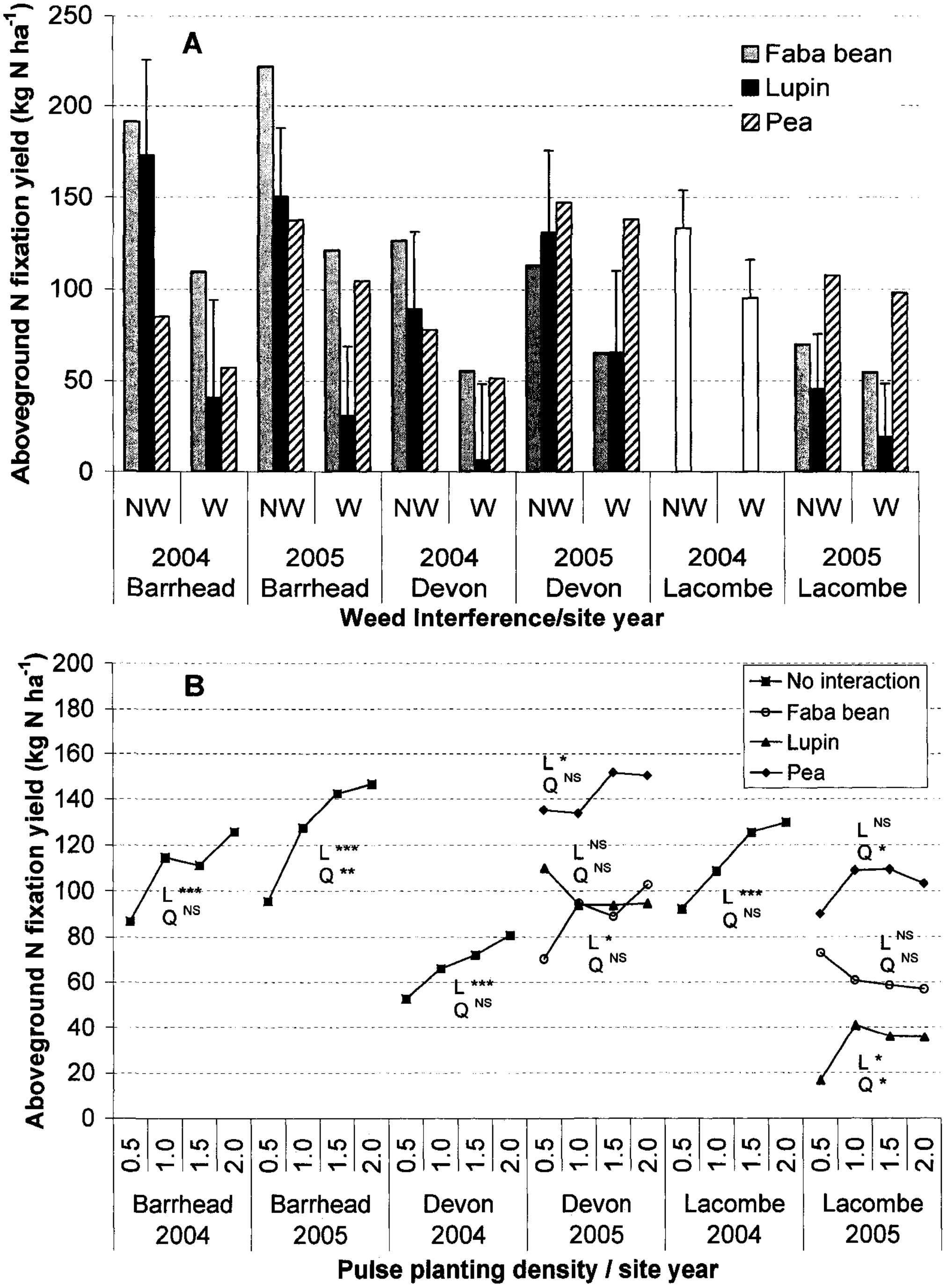

Figure 3-3. Aboveground N-fixation yield of first year pulse crops at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005. (A) The top graph indicates the weed interference by pulse species interaction and (B) the bottom graph indicates the pulse species by PPD interaction when the interactions are significant in the ANOVA. When the interactions are not significant, weed interference (significant at all site–years, except Lacombe 2005) is shown as white bars and PPD (significant at all site–years when the interaction is not significant) is shown as black squares (■). No other interactions are significant. LSD $_{0.05}$ bars are different for each site–year, and apply to all pulse species. Pulse species are indicated by open circles (○, faba bean), solid triangles (▲, lupin), or solid diamonds (♦, pea). Abbreviations: L, significance of a linear trend; NW, nonweedy; PPD, pulse planting density; Q, significance of a quadratic trend; W, weedy.
*, **, ***, and NS indicate significance at $P < 0.05$, $P < 0.01$, $P < 0.001$, and not significant, respectively.

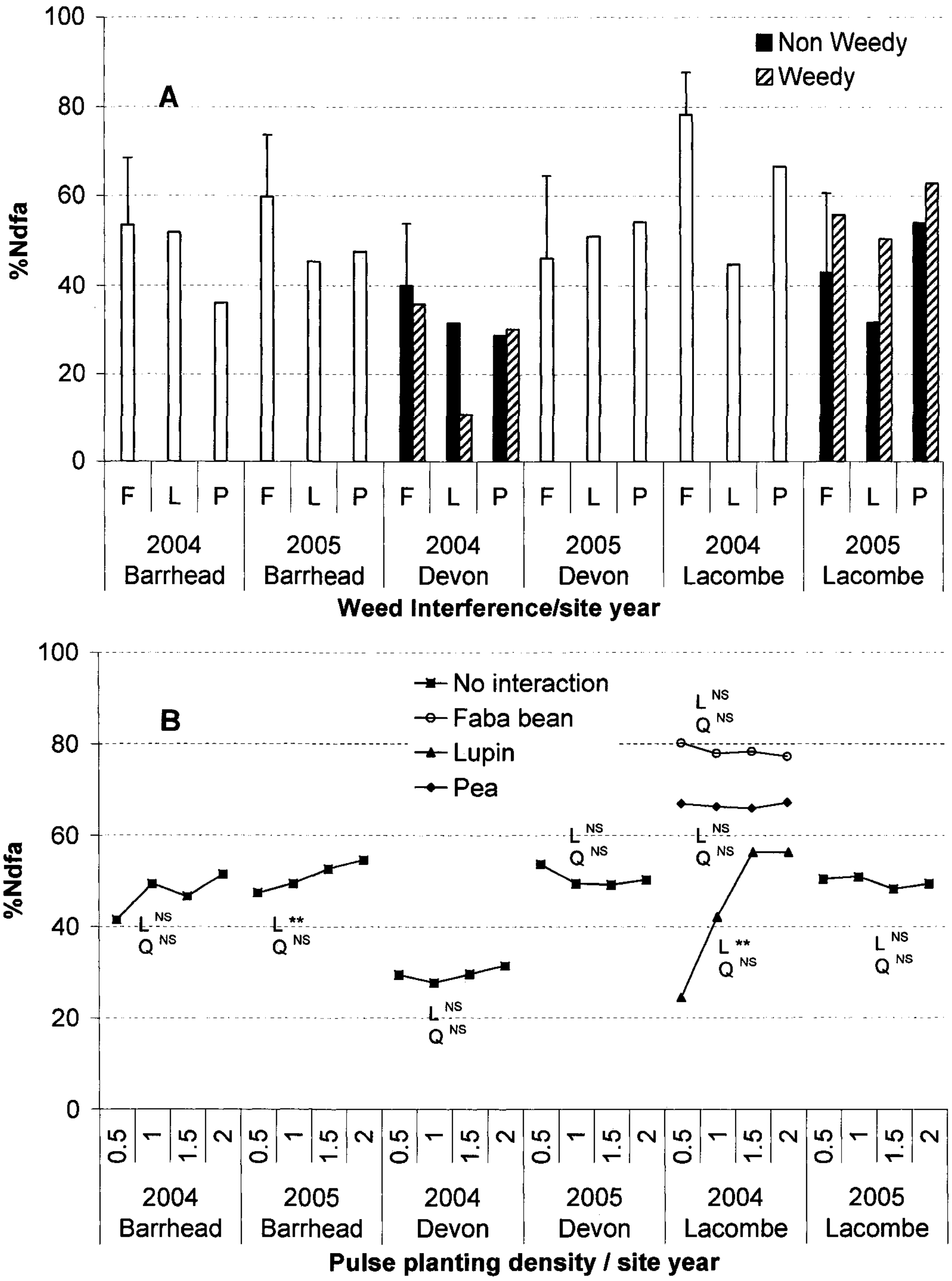

Figure 3-4. %Ndfa for first year pulse crops at Barrhead, Devon, and Lacombe, AB, Canada, in 2004 and 2005. (A) The top graph indicates the weed interference by pulse species interaction and (B) the bottom graph indicates the pulse species by PPD interaction when the interactions are significant in the ANOVA. When the interactions are not significant in graph A, pulse species (significant at all site–years, except Devon 2005) is shown as white bars. When the interactions are not significant in graph B, PPD (significant only at Barrhead 2005) is shown as black squares (■). No other interactions are significant. LSD $_{0.05}$ bars are different for each site–year, and apply to all pulse species. In graph B, pulse species are indicated by open circles (○, faba bean), solid triangles (▲, lupin), or solid diamonds (◆, pea). Abbreviations in graph A: F, faba bean; L, lupin; %Ndfa, percent nitrogen derived from the atmosphere; P, pea. Abbreviations in graph B: L, significance of a linear trend; PPD, pulse planting density; Q, significance of a quadratic trend; %Ndfa, percent nitrogen derived from the atmosphere. *, **, ***, and NS indicate significance at $P < 0.05$, $P < 0.01$, $P < 0.001$, and not significant, respectively.

Chapter 4

Long-term nitrogen release from faba bean, lupin, pea, and barley crop residues

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Chapter 4

Long-term nitrogen release from faba bean, lupin, pea, and barley crop residues

4.1 Introduction

Achieving sustainable crop production systems depends on producers adopting reduced tillage practices and diversifying crop rotations. Grain legumes, commonly known as pulse crops, can benefit crop rotations as they fix atmospheric nitrogen (N), and provide rotational benefits to subsequent crops (*Peoples* et al., 1995; *Stevenson* and *van Kessel*, 1996). On the Canadian prairies, cereal yields increased between 7 to 21% and cereal seed protein contents increased by 11% when wheat was grown on pulse stubble as compared to cereal stubble (*Gan* et al., 2003; *Wright*, 1990). Enhanced subsequent crop performance is commonly attributed to increases in soil N availability from the decomposition and mineralization of senesced pulse crop residues (*Peoples* et al., 1995).

In addition to climatic conditions, residue quality regulates the rate and extent of decomposition and N mineralization by soil organisms. In general, a high residue N content is associated with enhanced decomposition and N mineralization (*Janzen* and *Kucey*, 1988). High C:N ratios are negatively correlated with decomposition and N mineralization (*Ranells* and *Wagger*, 1996) as is lignin content, lignin:N ratio, polyphenol content, and polyphenol:N ratio

(*Paul* and *Clark*, 1996; *Kumar* and *Goh*, 2000). Pulse crop residues typically have low C:N ratios between 25:1 to 40:1 (*Stevenson* and *van Kessel*, 1996) and this generally results in rapid mineralization and significant increases in soil mineral N (*Karlen* et al., 1994).

There is evidence of producers adopting reduced tillage practices to improve sustainability. In Canada, no-till acres have increased from 30 to 46% between 2001 and 2006 (*Statistics Canada*, 2007) as producers recognize the economic (*Zentner* et al., 2002) and environmental benefits (*Lafond* and *Derksen*, 1996) of no-till farming. In order to optimize no-till production, it is important to understand nutrient release from decomposing residues left on the soil surface as they typically decompose more slowly than buried residues (*Harper* and *Lynch*, 1981; *Summerell* and *Burgess*, 1989; *Lupwayi* et al., 2004) which may affect nutrient availability to subsequent crops.

Due to the relatively slow nature of nutrient mineralization and dry matter (DM) breakdown, it is necessary to conduct long-term decomposition studies. However, the decomposition of agricultural crop residues is rarely studied beyond 12 months. In northern Alberta, over a 12-month period, *Lupwayi* et al. (2004) found that 43% of pea but only 27% of wheat DM decomposed under no-till. Under conventional tillage, 45 to 55% of pea and 40% of wheat DM decomposed. In addition, *Lupwayi* et al. (2006) reported that approximately 25% of pea and wheat N was released from decomposing crop residues in a 12-month period. Based on the substantial amount of N and DM remaining after 12 months of decomposition, there is potential for significant N mineralization and mass loss in subsequent months. However, mass loss and N mineralization rates cannot be extrapolated from short-term studies. As decomposition proceeds, there is an initial rapid loss of easily decomposable materials such as sugars, starches, and proteins (*Wieder* and *Lang*, 1982). Over time, the rate of decomposition declines which reflects a reduction in substrate quality (*Kumar* and *Goh*, 2000).

Diversifying crop rotations is difficult when there are few crop options. Traditionally, field pea (*Pisum sativum* L.) has been the only pulse crop grown in the Parkland region of Alberta. However, within the past 5 years tannin-free faba bean (*Vicia faba* L.) production has increased due to its lack of anti-nutritional factors, high energy, high protein, high yields, and similar production costs relative to field pea (*Lopetinsky*, personal communication). A second cool season pulse crop, narrow-leafed lupin (*Lupinus angustifolius* L.) is also showing promise as a new crop in the region. Farmers would be more willing to include new crop species in their rotations if they knew the N contribution of each species to their cropping systems.

Insight into the role different pulse crops and reduced tillage can play in supplying biologically fixed N to subsequent crops can be gained by understanding mass loss and N mineralization from decomposing crop residues placed on the soil surface or buried at a depth of 5 cm. The objectives of this research were to determine (a) the effect of species and location on the rate and extent of residue decomposition and N release over a 22-month period, along with their effects on cumulative N release, and (b) the relationship between initial residue quality and residue decomposition rate.

4.2 Materials and methods

4.2.1 Site Characteristics, plant sampling, and analyses

This study was conducted as part of an existing field trial that was established in 2004 on a commercial farm near Barrhead, AB (54° 6'N, 114° 17'W). Soil was classified as an orthic humic Gleysol with a heavy clay texture (*Wynnyk* et al., 1969). Rainfall and temperature data were collected from an Environment Canada weather station located 11.4 km from the test site at 54° 5'N, 114° 21'W. The field trial was a strip-split-plot randomized complete block design with four blocks. Presence and absence of barley (*Hordeum vulgare* L.) was the strip-plot. Pulse species was the main plot and pulse planting density was the sub-plot. Agronomic practices for the field trial have been described in *Strydhorst* et al. (2008). Straw samples were collected from four treatments to assess initial residue quality, decomposition, and N release. The four treatments sampled for the current study were: sole crops of tannin-free faba bean 'Snowbird', narrow-leafed lupin 'Arabella', field pea 'Cutlass', and a barley 'Niobe' monoculture, sown to meet a target plant density of 45, 100, 75, and 210 plants m^{-2}, respectively.

In 2004, straw samples were hand harvested, at pulse crop physiological maturity, from a 0.4 m^2 quadrant. Pulse pods and barley heads were removed from the plants to simulate seed harvest. The remaining crop residues were dried at 40°C and weighed to determine straw yield. Dry crop residues were cut into 2.5 cm lengths, to simulate straw chopping, and 10 g of dry material was placed in litterbags (18 cm x 21 cm) constructed from 1-mm fiberglass mesh material on the upper side and nylon fabric on the lower side. We modified traditional litterbag construction by placing nylon fabric on the bottom of the litterbag to prevent fine residue loss. This was particularly important for a long-term study as *Kumar* and *Goh* (2000) cite loss of particulate matter to be the dominant source of mass loss in late stages of mesh bag decomposition studies.

Litterbags were returned to the field, approximately three weeks after crop residue harvest, and placed onto their respective stubble types. Placing crop residues in their respective stubble types allowed residues to decompose in their native soil nutrient and microbial environment. Pea and barley litterbags were returned to the field September 17, 2004. Faba bean and lupin litterbags were returned to the field October 5, 2004. Different placement times reflect different crop maturity dates. Litterbags were placed on the soil surface or buried at a depth of 5 cm. Surface placed litterbags were secured to the ground with a 20-cm spike. For each residue type, there were forty litterbags corresponding to two placement locations, five sample removal times, and four replicates. The decomposition area remained unseeded throughout 2005 and 2006. Weeds were controlled with biannual applications of glyphosate at 440 g ai ha^{-1} and hand weeding. Litterbags were collected five times over a 22-month period on: April 21, 2005, August 2, 2005, September 29, 2005, April 24, 2006, and July 25, 2006. These dates correspond to major cropping events: seeding 2005, silage harvest 2005, seed harvest 2005, seeding 2006, and silage harvest 2006, respectively.

Retrieved litterbags were dried at 40°C and weighed to determine mass loss. Subsamples of the initial crop residues and materials from the litterbags were ground with a Wiley mill to 1 mm and dried overnight at 550°C to determine percent ash-free DM. All plant constituents were reported on an ash-free basis, as were litter masses, to correct for any field soil contamination (*Blair*, 1988). Nitrogen and C contents of the plant samples were determined using a LECO C and N-analyzer (TruSpec CN Determinator, Leco Corp., St Joseph, MI). Neutral detergent fibre (NDF), acid detergent fibre (ADF), and acid detergent lignin (ADL) analyses of the initial crop residues were conducted using batch procedures outlined by ANKOM Technology Corporation (Fairport, NY) for an ANKOM200 Fiber Analyzer (*Komarek*, 1993; *Komarek*, et al. 1994). Hemicellulose was calculated as the difference between NDF and ADF, cellulose was calculated as the difference between ADF and ADL, while lignin was considered to be equivalent to ADL.

4.2.2 Data analysis

All data were tested for normality using PROC UNIVARIATE (*SAS Institute*, 2003). The analysis indicated that transformations were necessary for some data. Initial N, hemicellulose, and N yield data were $\log_{10}(x+1)$ transformed. Analysis of variance was performed on the initial quality data with the MIXED procedure of SAS (*Littell* et al., 2006). Crop residue type was considered fixed and block was considered random. The NOBOUND option was used with the C, lignin, and lignin:N data to gain better control over Type I error and improve power as the block variance component was zero without this option (*Littell* et al., 2006). Initial residue quality means were separated by the Tukey-Kramer method when ANOVA indicated significant crop residue effects at 5% significance level. Simple correlation analysis was conducted to quantify relationships between initial residue quality (chemical characteristics) and decomposition parameters (%DM remaining, %N remaining and N released).

Percent DM remaining and % N remaining data were $(x+0.5)^{0.5}$ transformed. A repeated measures ANOVA was performed on the %DM remaining, %N remaining, and N release data with the MIXED procedure of SAS (*Littell* et al., 2006). Block was considered a random effect while crop residue type, decomposition location, and sampling time were considered fixed.

Attempts were made to fit nonlinear, quadratic, and linear regression models to mean values of the DM and N remaining data at each sampling date. Linear regression equations fit to natural log transformed DM and N remaining data resulted in the best fit. To determine the number of days it took for crop residues to release 50% of their initial DM and N, regression equations were solved when y equaled 50% of the initial DM and N.

4.3 Results and discussion

From the initiation of the study until April 2005, the site received 87 mm more precipitation than the 30-yr average (145 mm) and average temperatures were -

3.3°C compared to the 30-yr average of -5.5°C, making the first seven months of the study warmer and wetter than the 30-yr average. Summer 2005 was drier than the 30-yr average (342 mm) with the site receiving 283 mm of precipitation but temperatures were near 30-yr average temperatures of 12.9°C. In the spring of 2006, the site received 39 mm more than the 30-yr average of 86 mm and temperatures were 4.7°C compared to the 30-yr average of 3.3°C, resulting in warmer and wetter conditions.

4.3.1 Characteristics of initial crop residues

With the exception of N yield and C content, all initial characteristics differed among residue types (Tab. 4-1). Nitrogen contents (18.9, 19.0, 26.0, and 19.5 mg g^{-1} for barley, faba bean, lupin, and pea, respectively) were greater than reported values (4.3–10.8, and 4.2–7.9 mg g^{-1} for pea and wheat, respectively) for similar crops grown in northern environments (*Soon* and *Arshad*, 2002; *Lupwayi* et al., 2004). This may be attributed to the study being conducted on a soil with high organic matter (86–97 g kg^{-1}) compared to other studies where soil organic matter levels [1.72 x soil organic C] were 43 g kg^{-1} (*Lupwayi* et al., 2004), or 63 g kg^{-1} (*Soon* and *Arshad*, 2002). Greater N release from organic matter mineralization at our experimental site could have provided larger amounts of N to growing crops. Lupin residues had the highest N content and lowest C:N ratio and were therefore expected to decompose rapidly (*Janzen* and *Kucey*, 1988). Barley, faba bean, and pea residues had similar N contents and C:N ratios.

Barley residues had higher cellulose and hemicellulose contents compared to pulse residues (Tab. 4-1). Faba bean and pea had high lignin contents and lignin:N ratios, lupin had intermediate levels, while barley had low levels. Similar trends for legumes and cereals have been reported by *Koenig* and *Cochran* (1994) and *Ranells* and *Wagger* (1996). High lignin levels would be expected to slow pulse decomposition (*Paul* and *Clark*, 1996) however, due to the different nature of cereal and legume lignin linkages, barley lignin is more resistant to decomposition than pulse lignin (*Van Soest*, 1964).

The N yield [DM production x N content] is the total amount of N available for release from decomposing residues. Although differences were not significant, lupin had the highest N yield, followed by barley and faba bean, while pea had the least (Tab. 4-1). Pulse N yields were within the range of reported values (*Beck* et al., 1991; *Maidl* et al., 1996; *Ayaz* et al., 2004; *Armstrong* et al., 1997; *Soon* et al., 2004). The barley N yield was higher than expected due to a high N content and high DM production. Barley residue N yields of 11–45 kg N ha^{-1} have been reported in other Alberta studies (*Soon* et al., 2004; *Izaurralde* et al., 1990).

4.3.2 Rate and extent of residue decomposition

The repeated measures ANOVA of %DM remaining indicated that all factors, with the exception of the residue type by decomposition location interaction, were significant (Tab. 4-2). Sampling time accounted for most variation. The decomposition location by sampling time interactions, for %DM remaining, are further illustrated in Fig. 4-1. After the first winter (198 or 216 days after field placement) 53 to 81% DM remained, depending on the residue type and decomposition location. In Alaska, *Koenig* and *Cochran* (1994) reported that 60 to 70% DM remained after decomposition of similar residue types between October and May. They attributed much of the mass loss to leaching of water-soluble materials. Traditionally, organic matter decomposition has been considered negligible during the winter period when soil temperature is close to or below 0°C (*Chantigny* et al., 2002). However, microbial activity in frozen soils may contribute to significant levels of decomposition (*Dorland* and *Beauchamp*, 1991). This is confirmed by the current study results, where decomposition losses between litterbag placement (September 17, 2004 or October 5, 2004) and the first collection in April 2005 represented 28 to 44% of the total DM losses measured during the first year of study (i.e., until September 29, 2005).

All residues decomposed faster and more extensively when buried 5 cm deep compared to surface placement (Fig. 4-1). Based on the log linear regression equations, surface placed and buried residues had 50% DM remaining after 260–479 and 129–218 days of decomposition, respectively, depending on the crop residue type (Tab. 4-3). Surface placed DM remaining regression equations explained only 57 to 86% of the variance associated with decomposition. However, plots of the actual data (Fig. 4-1), indicated that surface placed decomposition was still much slower than buried residue decomposition. By the end of the study (22 months), buried residues had a mean 5% DM remaining and surface placed residues had a mean 43% DM remaining. More rapid and extensive decomposition of buried residues has been attributed to increased residue-soil contact (*Summerell* and *Burgess*, 1989), and greater access of soil decomposing microorganisms to crop residues (*Harper* and *Lynch*, 1981). The belowground environment also buffers temperature and moisture fluctuations (*Summerell* and *Burgess*, 1989) and allows microorganisms greater access to soil nutrients (*Harper* and *Lynch*, 1981), which would enhance their activity.

The long-term nature of this study allowed us to test the hypothesized long-term decomposition pattern proposed by *Lupwayi* et al. (2004). *Lupwayi* et al. (2004) observed an initial rapid drop in %DM remaining, in both surface placed and buried residues, at the beginning of their study and then a second drop in %DM remaining one year after residue placement. They hypothesized that a second rapid phase of decomposition would occur the following year. The current study indicated rapid decomposition of surface placed and buried residues during the first 365 days of decomposition (Fig. 4-1). In the second year, buried residues decomposed more rapidly than surface placed residues. These findings support the hypothesized decomposition pattern proposed by *Lupwayi* et al. (2004) for buried residues, but not for surface placed residues.

Days to 50% DM remaining (Tab. 4-3) can be used to compare decomposition among residue types. Lupin decomposed most rapidly, requiring 129–260 days to reach 50% DM remaining, depending on the decomposition location. Rapid lupin residue decomposition was expected based on its high initial N content and low C:N ratio (Tab. 4-1). By the second spring (566 days after field placement) buried lupin residues had completely decomposed. Other authors have reported faster lupin decomposition compared to other crop residue types (*Cookson* et al., 1998; *Mayer* et al., 2004) and partially attributed this to greater bacteria and fungal hyphae populations on lupin residues compared to other residue types (*Cookson* et al., 1998). Barley, faba bean, and pea required 218–479, 196–422, and 218–424 days, respectively, to reach 50% DM remaining, depending on the decomposition location (Tab. 4-3). Similar barley, faba bean, and pea decomposition rates may be attributed to similar initial N contents and C:N ratios. In support of this, *Mayer* et al. (2004) examined pulse residue decomposition in a 24-week greenhouse study and reported similar decomposition rates due to similar initial residue qualities. In agreement with other authors (*Janzen* and *Kucey*, 1988; *Soon* and *Arshad*, 2002; *Lupwayi* et al., 2004), we found that high initial N contents and low C:N ratios were associated with rapid DM loss. Lignin contents were not good predictors of pulse and barley decomposition rates since pulses and barley have different portions of their dry matter lignified (*Van Soest*, 1964) which may affect decomposition.

4.3.3 Rate and extent of N release

The repeated measures ANOVA of %N remaining indicated that residue type, decomposition location, sampling time, and their interactions were significant (Tab. 4-2). Sampling time accounted for most variation. The interaction of decomposition location and sampling time, for %N remaining, are further illustrated in Fig. 4-2. For approximately the first 300 days of decomposition, surface placed and buried residues had similar rates of N release. Initial N loss was likely due to release of soluble and readily decomposable amino sugars, nucleic acids, and proteins (*Paul* and *Clark*, 1996). After approximately 400 days of decomposition, buried residues released N more rapidly and extensively than surface placed residues (Fig. 4-2). In some instances, surface placed residues increased their N content. In northern Alberta, *Lupwayi* et al. (2006) reported rapid N release in the initial stages of decomposition but little further N release thereafter as recalcitrant constituents such as lignin, condensed tannins, and other polyphenols were assumed to remain in the residues. More extensive N release, from buried residues in later stages of decomposition, may be attributed to more stable temperature and moisture conditions (*Summerell* and *Burgess*, 1989) which would favor microbial activity and enhance microbial degradation of recalcitrant materials. However, slower N release from surface placed residues may be desirable as there may be fewer opportunities for N loss during the non-growing season.

Days to 50% N remaining (Tab. 4-3) can be used to compare N release among residue types. Lupin, faba bean, barley, and pea residues had 50% N remaining after 112–166, 172–238, 219–294, and 229–290 days of decomposition, respectively, depending on decomposition location. By the end of the study, lupin released a significantly larger percentage of its initial N (92%) compared to other residue types (mean 81%). The rapid and extensive N release from lupin residues was expected due to its high initial N content. Other authors (*Janzen* and *Kucey*, 1988; *Lupwayi* et al., 2006) have reported strong correlations between initial N content and N mineralization.

4.3.4 N release during decomposition and potential N supply to subsequent crops

To understand the N contribution of decomposing residues to subsequent crops, it was necessary to quantify the amount of N released by each residue type [(100 - %N remaining) x initial N yield]. Nitrogen not remaining in residues was assumed to be mineralized and released into the soil. The repeated measures ANOVA of N released indicated that all factors were significant (Tab. 4-2). Sampling time and residue type accounted for most variation. The interaction of decomposition and sampling time for the cumulative amount of N released is further illustrated in Fig. 4-3.

Following pulse crop harvest, there is a period of asynchrony between N supply from decomposing residues and subsequent crop N demand (*Crews* and *Peoples*, 2005). In northern environments significant leaching of water soluble compounds, arising from decomposing crop residues, has been reported during the rapid spring snowpack thaw (*Koening* and *Cochran*, 1994). In Denmark, *Jensen* (1994a) found that without growing plants to take up N released from decomposing residues, between 9 and 17% of the input ^{15}N was leached as nitrate below a 45-cm soil depth in the first 180 days of decomposition. However, this problem can be lessened by lowering the rates of N release. Over the first winter (198 to 216 days after field placement), decomposing pea and lupin residues released 28 and 67 kg N ha^{-1}, respectively (Fig. 4-3). If 10% of the released N was subject to leaching and denitrification loss, pea residues would lose only 2.8 kg N ha^{-1} while lupin residues would loose more than twice as much N (6.7 kg N ha^{-1}).

At the subsequent crop grain harvest (359 to 377 days after field placement), barley, faba bean, lupin, and pea released 74–80, 62–76, 118–134, and 54–57 kg N ha^{-1}, respectively, depending on decomposition location (Fig. 4-3). In northern Alberta litterbag studies, after 12-months of pea residue decomposition, *Lupwayi* et al. (2006) reported N release of 4–18 kg N ha^{-1} while *Soon* and *Arshad* (2002) reported -0.9–12.1 kg N ha^{-1}. Greater N release in this study can be primarily attributed to higher N yields (Tab. 4-1).

Given that spring wheat removes 95 kg N ha^{-1} yr^{-1} in typical Alberta cropping systems (*Alberta Agriculture and Food*, 2000), decomposing crop residues could theoretically supply a significant portion of a subsequent wheat crop's N requirements. If all of the N released from decomposing residues, by the silage harvest 2005 sampling time (301–319 days after placement in the field), was available for crop uptake, lupin, faba bean, barley, and pea residues could supply 125, 71, 68, and 45% of a subsequent wheat crop's N needs, respectively. However, much of the N released from decomposing crop residues has not been traced to the subsequent crop (*Bremer* and *van Kessel*, 1992; *Jensen*, 1994a). Rather it has been found primarily in soil microbial biomass and recalcitrant soil organic matter (*Jensen*, 1994b; *Mayer* et al., 2004). In this form, the N can be gradually mineralized for use by future crops and can increase long-term soil fertility (*Kumar* and *Goh*, 2002).

4.5 Conclusions

Slower DM and N loss from surface placed residues, compared to buried residues, demonstrates the patterns of nutrient release in no-till and conventional-till farming systems. In this long-term decomposition study, we observed rapid decomposition of buried residues over the 22-month study period which supports the hypothesized decomposition pattern proposed by *Lupwayi* et al. (2004) for residues decomposing under conventional-till. In contrast, surface placed residues experienced relatively faster rates of decomposition and N loss in the first year of decomposition compared to the second year of decomposition. Slow N release in no-till systems, over the long-term, can be desirable as there may be fewer opportunities for N loss.

Tannin-free faba bean and narrow-leafed lupin crop residues have the potential to supply more N to subsequent crops compared to pea crop residues. Lupin residues decomposed and released N more rapidly and extensively than other residue types, as predicted by its high initial N content and low C:N ratio. Barley, faba bean, and pea decomposed at similar rates likely due to their similar initial N contents and C:N ratios. Based on these findings, lupin and faba bean would be expected to make significantly greater N contributions to subsequent crops compared to pea. However, a full assessment of lupin and faba bean N contributions to subsequent crops will require an investigation of N loss and N partitioning to soil microbial biomass and recalcitrant soil organic matter as the timing of N release from decomposing crop residues does not appear to coincide well with the timing of subsequent crop N uptake.

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Table 4-1: Nitrogen yield and initial chemical characteristics (reported on an ash-free basis) of barley, faba bean, lupin, and pea aboveground crop residues grown at Barrhead, AB in 2004.

Residue type	N yield[a] (kg N ha^{-1})	N[a] (mg g^{-1})	C (mg g^{-1})	C:N ratio	Hemicellulose[a] (mg g^{-1})	Cellulose (mg g^{-1})	Lignin (mg g^{-1})	Lignin:N ratio
Barley	108	18.9 b	495	26.6 a	302 a	374 a	38 b	2.0 c
Faba bean	94	19.0 b	491	25.9 ab	89 c	255 bc	103 a	5.4 a
Lupin	138	26.0 a	498	20.1 b	120 b	210 c	63 ab	2.6 bc
Pea	77	19.5 ab	502	25.9 ab	131 b	306 b	91 a	4.7 ab
Residue type effect[b]	ns	*	ns	*	***	***	**	**
SE	23.2	2.2	4.5	2.0	12.1	19.9	13.1	0.7

Values within one column followed by the same letter are not significantly different at $P<0.05$ as determined by a Tukey-Kramer means separation test.
SE standard error of the difference between residue types (n=16).

[a] Data were transformed to $\log_{10}(x+1)$, and original means are presented here.

[b] Main effect of all treatments; *, **, ***, and ns significant at $P<0.05$, 0.01, 0.001, and not significant, respectively.

Table 4-2: Summary of treatment effects on %DM remaining, % N remaining, and N released from crop residues decomposing at Barrhead, AB between fall 2004 and summer 2006.

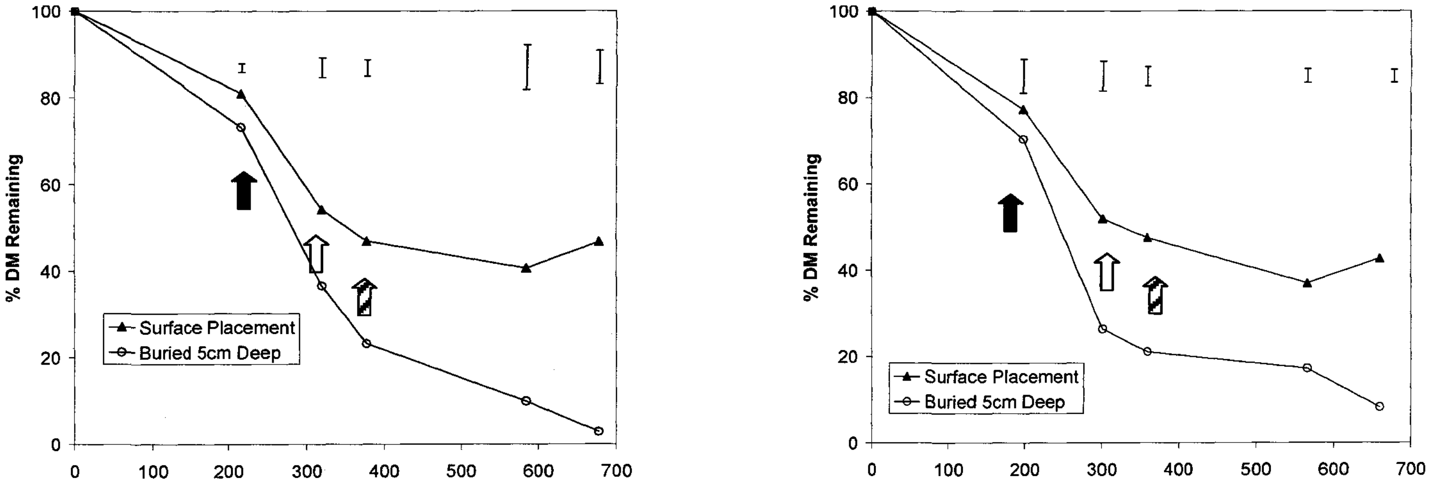
Treatment Effect	F value		
	% DM Remaining	% N Remaining	N released
Residue Type	12.42 ***	18.04 ***	224.77 ***
Decomposition Location	268.04 ***	86.39 ***	82.53 ***
R x L	2.71 ^{ns}	4.20 *	5.69 *
Sampling Time	304.64 ***	328.47 ***	739.86 ***
R x T	2.96 ***	3.16 ***	23.52 ***
L x T	36.89 ***	18.02 ***	9.58 ***
R x L x T	2.42 **	2.28 **	2.60 **

Significance of main effects and interactions; *, **, ***, and ns significant at $P<0.05$, 0.01, 0.001, and not significant, respectively.
DM dry matter, *L* decomposition location, *R* residue type, *T* sampling time.

Table 4-3: Results of fitting linear regression equations to natural log transformed DM remaining and N remaining data. Regression equations, R^2, and days to 50% DM remaining or 50% N remaining as calculated from the linear regression equations for barley, faba bean, lupin, and pea residues decomposing on the soil surface or buried at a depth of 5 cm.

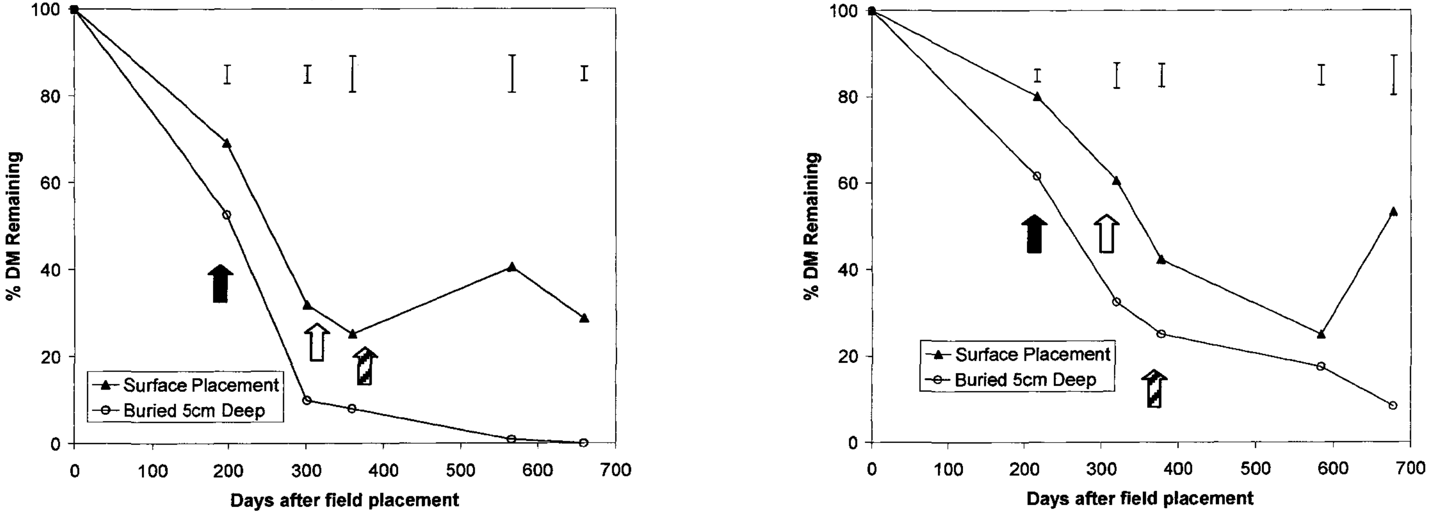
		DM remaining			N remaining		
Decomposition location	Residue type	Regression equation	R^2	Days to 50%	Regression equation	R^2	Days to 50%
Surface	Barley	y = 2.23 – 0.00130 d	0.81 *	479	y = 2.72 – 0.00162 d	0.68 *	294
	Faba bean	y = 2.22 – 0.00146 d	0.86 **	422	y = 2.91 – 0.00277 d	0.96 ***	238
	Lupin	y = 2.05 - 0.00171 d	0.57^{ns}	260	y = 3.01 – 0.00268 d	0.73 *	166
	Pea	y = 2.26 - 0.00153 d	0.65^{ns}	424	y = 2.87 – 0.00204 d	0.69 *	290
Buried	Barley	y = 2.74 - 0.00518 d	0.92 **	218	y = 3.29 – 0.00475 d	0.92 **	219
	Faba bean	y = 2.33 – 0.00368 d	0.92 **	196	y = 2.92 – 0.00391 d	0.95 ***	172
	Lupin	y = 2.72 – 0.00862 d	0.95 **	129	y = 3.66 – 0.00977 d	0.96 **	112
	Pea	y = 2.38 – 0.00353 d	0.96 ***	218	y = 3.07 – 0.00347 d	0.97 ***	229

Significance of R^2; *, **, ***, and ns significant at $P<0.05$, 0.01, 0.001, and not significant, respectively.
d days after field placement, *DM* dry matter.



(a) Barley

(b) Faba bean



(c) Lupin

(d) Pea

Figure 4-1

Figure 4-1: Decomposition, as indicated by %dry matter (DM) remaining (reported on an ash-free basis), of barley, faba bean, lupin, and pea crop residues placed on the soil surface or buried to a depth of 5cm over a period of 659 or 677 days at Barrhead AB between fall 2004 and summer 2006. Arrows indicate times of major cropping events, ⬇ = subsequent crop seeding (May 2005), ⇩ = subsequent crop silage harvest (August 2005), and ⇓ = subsequent crop grain harvest (September 2005). Bars indicate standard error of difference between residues placed on the soil surface or buried at 5 cm depth, at each sampling date (n=8).

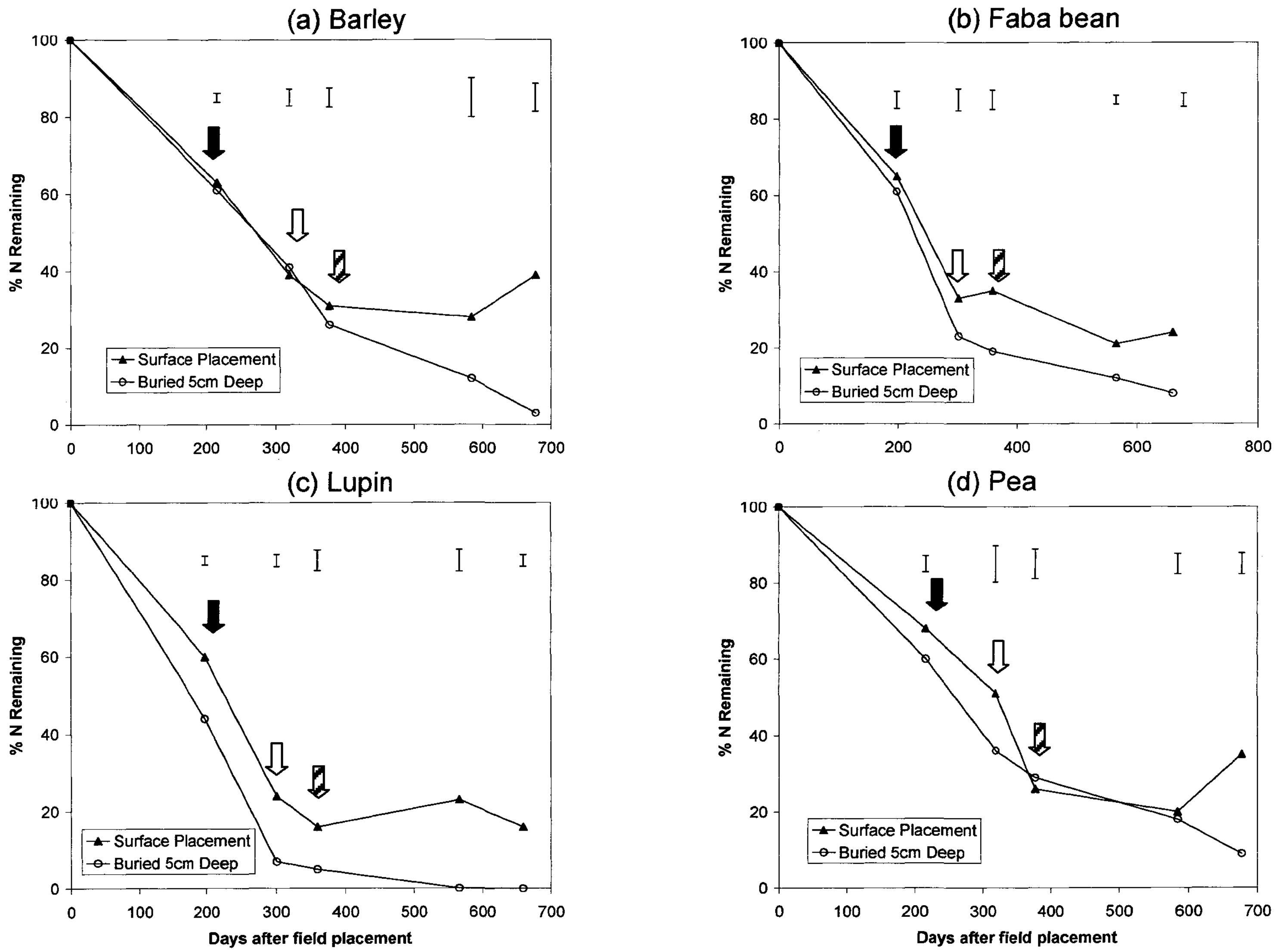

(a) Barley
(b) Faba bean
(c) Lupin
(d) Pea
% N Remaining
Days after field placement
Surface Placement
Buried 5cm Deep
0
20
40
60
80
100
0
100
200
300
400
500
600
700
800

Figure 4-2

Figure 4-2: Percentage of initial N remaining (reported on an ash-free basis) in barley, faba bean, lupin, and pea crop residues placed on the soil surface or buried to a depth of 5 cm over a period of 659 or 677 days at Barrhead AB between fall 2004 and summer 2006. Arrows indicate times of major cropping events, ⬇= subsequent crop seeding (May 2005), ⇩= subsequent crop silage harvest (August 2005), and ⇓ = subsequent crop grain harvest (September 2005). Bars indicate standard error of difference between residues placed on the soil surface or buried at 5 cm depth, at each sampling date (n=8).

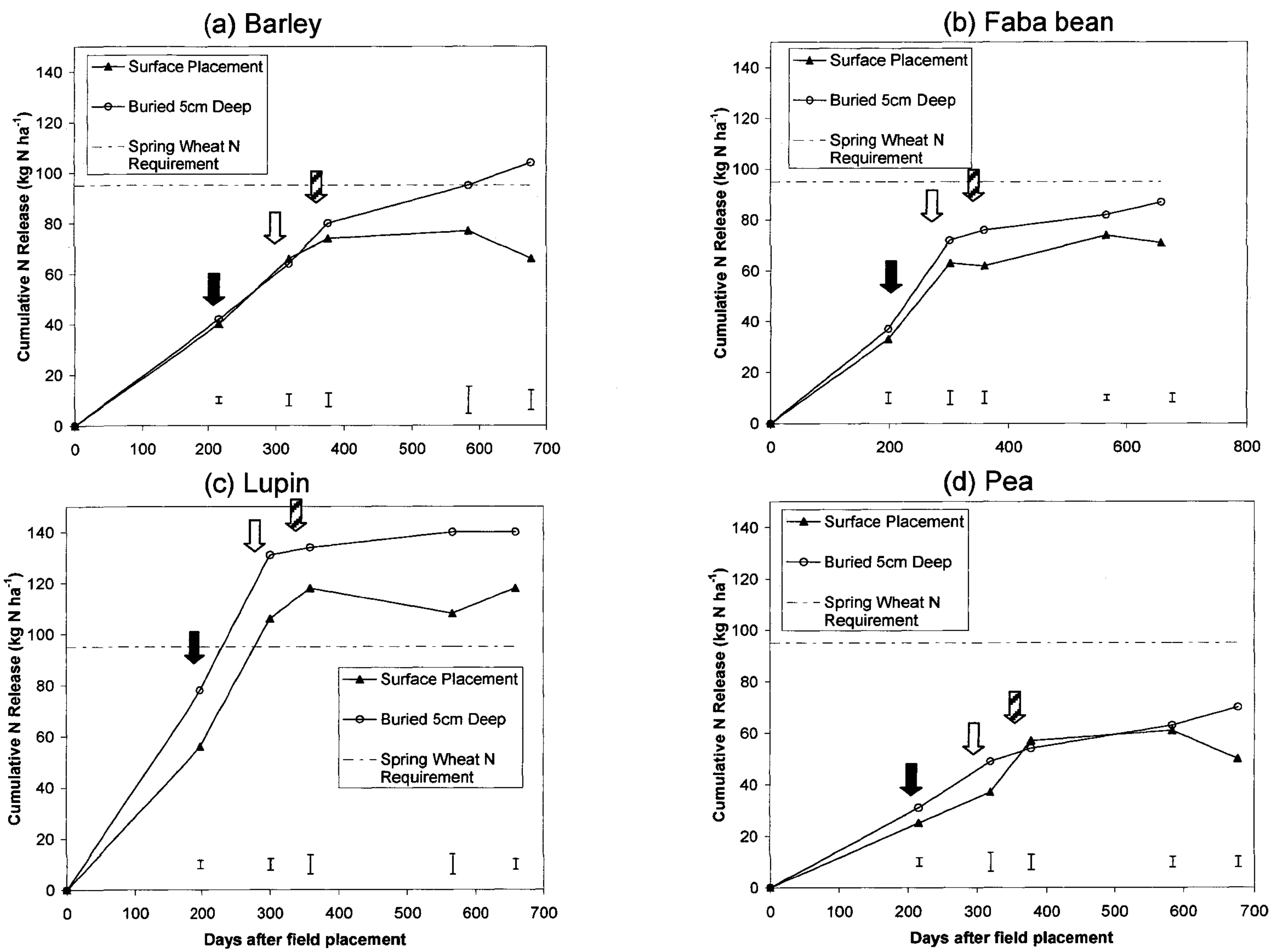

(a) Barley
(b) Faba bean
(c) Lupin
(d) Pea
Surface Placement
Buried 5cm Deep
Spring Wheat N Requirement
Cumulative N Release (kg N ha^{-1})
Days after field placement
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700
800

Figure 4-3

Figure 4-3: Cumulative N release (reported on an ash-free basis) from barley, faba bean, lupin, and pea crop residues placed on the soil surface or buried to a depth of 5 cm over a period of 659 or 677 days at Barrhead AB, between fall 2004 and summer 2006, along with the N requirements of a spring wheat crop. Arrows indicate times of major cropping events, ⬇ = subsequent crop seeding (May 2005), ⇩ = subsequent crop silage harvest (August 2005), and ⇓ = subsequent crop grain harvest (September 2005). Dashed line indicates the N removal of a spring wheat crop (95 kg N ha^{-1} yr^{-1}) in typical Alberta cropping systems (*Alberta Agriculture and Food*, 2000). Bars indicate standard error of difference between residues placed on the soil surface or buried at 5 cm depth, at each sampling date (n=8).

Chapter 5

The role of N cycling in grain legume-wheat cropping sequences

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Chapter 5

The role of N cycling in grain legume-wheat cropping sequences

Numerous studies have documented improved yield and quality of crops grown on grain legume stubble. On the Canadian prairies, cereal yields increased between 7 to 20% and cereal seed protein concentrations increased by 11% when wheat was grown on grain legume stubble as compared to cereal stubble (Gan et al., 2003; Wright, 1990a). Enhanced subsequent crop performance is commonly attributed to improved N availability which may result from: (i) N sparing by the grain legume crop (Hardarson and Atkins, 2003), (ii) N mineralized from senesced leaves, roots, or nodules (Peoples et al., 1995), and (iii) rhizodeposition of biologically fixed N (Sawatsky and Soper, 1991).

Differences in grain legume crop dry matter (DM) production, N accumulation, N fixation, N balance, and residue quality are thought to be the main factors determining the residual N contribution to subsequent crops (Mayer et al., 2003). However, most estimates of N fixation and soil N balance are based solely on aboveground plant biomass, even though most aboveground N is removed in harvested grain and/or straw (Evans et al., 2001; van Kessel and Hartley, 2000). Russell and Fillery (1996) found that lupin root N represents 28% of total plant N, Armstrong et al. (1994) determined that pea root N represents 7 to 10% of total plant N at maturity, while Khan et al. (2003) estimates that faba bean and barley roots contain 24 and 36% of total plant N, respectively. It is critical to account for both aboveground and belowground N when determining residual N contributions to subsequent crops.

Measuring the amount of plant available N arising from organic sources is problematic. The amount of mineralizable N can be quantified with slow and laborious incubation experiments (Campbell, 1993). Rennie and Rennie (1983) suggest that the best estimation of plant available N is to allow a plant to sample for itself as it is difficult to obtain a soil sample which will give a representative measure of available soil N over the entire growing season. However, the methods described above cannot predict the amount of plant available N present in organic amendments. This information is needed to estimate N fertilizer requirements prior to planting a subsequent crop.

Labile soil N represents the soil N fraction that is easily and rapidly cycled. Accurate measurements of this soil fraction may be useful in predicting the amount of plant available N remaining after a grain legume crop is grown. Soil microbial biomass N (MBN) is a pool of soil N that rapidly changes following the growth of grain legumes. For instance, during the initial decomposition of incorporated pea residues, Jensen (1994) found that MBN almost doubled. In the following spring, MBN peaked and then fell to initial levels after 1yr of decomposition. In Saskatchewan, Canada, Stevenson and van Kessel (1996) found that 63% of the ^{15}N from labeled pea residues was recovered in the microbial biomass, in the spring following residue incorporation. In a greenhouse study, Mayer et al. (2003) found that N in a subsequent wheat crop could be traced to grain legume crop N that had been temporarily immobilized in the soil microbial biomass.

Soluble organic nitrogen (N extracted from soil by water or salt solutions) is also considered a relatively labile fraction of soil organic matter (Murphy et al., 2000). Soluble pools of organic N are comprised of easily mineralizable N and have a major impact on rapidly cycling mineral N pools (Mengel et al., 1999). Murphy et al. (2000) indicates that soluble organic N is an important pool in N transformation pathways and plant uptake.

Although soil MBN and soluble organic N are rarely investigated in studies attempting to quantify the rotational benefits of grain legume crops to subsequent crops, the above studies indicate the importance of these factors for short term N storage and cycling.

As inorganic N fertilizer becomes more expensive, due to higher manufacturing and transport costs, there is renewed interest in the use of legumes to supply a portion of the N to the cropping system. Annual N fixation rates of faba bean (8-352 kg N ha^{-1}) (Rochester et al. 1998) and lupin (95-283 kg N ha^{-1}) (Unkovich et al. 1995) can exceed that of pea (33-246 kg N ha^{-1}) (Beck et al. 1991, Maidl et al. 1996) and may contribute substantial N rotational benefits to the subsequent crop. However, the amount of grain legume N available to subsequent crops must be quantified to effectively use grain legumes as a N source in cropping systems. To obtain a quantitative measure of the effects tannin-free faba bean, narrow-leafed lupin, field pea and barley have on soil fertility, an N balance is required that measures the total (aboveground and belowground) amount of N fixed by the grain legume, the amount of soil N taken up, the amount of N removed in the harvested crop materials, the amount of N contained within the root materials, and the amount of N transferred to soil labile N pools and the subsequent crop. The objectives of this study were to: (i) develop a comprehensive N balance for faba bean, lupin, and field pea crops grown in the Parkland region of Alberta, Canada, (ii) calculate the amount of plant available N and agronomic utility of prior grain legume crops, as measured by a subsequent wheat crop, and (iii) establish the value of soil labile N measurements as predictors of plant available N.

MATERIALS AND METHODS

Two replications of a 2yr field experiment were conducted on a commercial farm near Barrhead, AB (54°6'N, 114°17'W) in the Parkland region of north central Alberta, Canada, between 2004 and 2006. Grain legumes and barley were grown in yr1 (2004, 2005) and wheat was grown on all yr1 plots in yr2 (2005, 2006). The soil was characterized as an Orthic Humic Gleysol (mesic Typic Endoaquoll) with a heavy clay texture (Wynnyk et al., 1969). Prior to seeding first year crops, soil chemical characteristics (to a depth of 30 cm) were assessed by an accredited testing laboratory (Bodycote Testing Group, 7217 Roper Road NW, Edmonton, AB). Organic matter, as measured by loss on ignition, ranged from 86 to 97 g kg^{-1} in 2004 and from 54 to 114 g kg^{-1} in 2005.

Soil pH, measured on a saturated paste extract, ranged from 6.3 to 6.4 in 2004 and from 6.3 to 6.7 in 2005. Soil nitrate N, extracted with a 0.001M $CaCl_2$ aqueous extractant, ranged from 12 to 18 mg kg^{-1} in 2004 and from 6 to 17 mg kg^{-1} in 2005. Soil phosphorus and potassium were extracted with a modified Kelowna solution. Less than 5 mg kg^{-1} of extractable phosphorous was measured in 2004 while 5 to 7 mg kg^{-1} was measured in 2005. Potassium ranged from 192 to 219 mg kg^{-1} in 2004 and from 207 to 257 mg kg^{-1} in 2005. Soil sulphate S, extracted with a 0.001M $CaCl_2$ aqueous extractant, was 5 mg kg^{-1} in 2004 and ranged from 3 to 5 mg kg^{-1} in 2005. Rainfall and temperature data were collected from an Environment Canada weather station located 11.4 km from the test site at 54° 5'N, 114° 21'W.

First year crop field experiment

The experimental design was a randomized complete block with four blocks. Four rotations, which were part of a larger study, comprised the treatments for the current study. These include first year grain legume crops: 'Snowbird' tannin-free faba bean, 'Arabella' narrow-leafed lupin, and 'Cutlass' field pea. 'Niobe' barley was included as a first year cereal crop. Faba bean, lupin, pea, and barley were seeded to meet recommended target plant populations of 45, 100, 75, and 210 plants m^{-2}, respectively (Alberta Agriculture and Food, 2001).

First year crops were seeded 3 May 2004 and 4 May 2005. Individual sub-plots were 2.4 m x 6 m. Plots were seeded in 12 rows with a small-plot-hoe drill at 20-cm row spacing. For each grain legume species, peat-based-granular inoculant, containing the appropriate *Rhizobium* bacteria, was placed in the furrow. All grain legumes were seeded at the same seeding depth, with actual depths varying between 5 and 7.5 cm depending on soil moisture conditions. Phosphorous (triple superphosphate), K (potassium chloride), and S (elemental sulfur) were applied to all treatments in the spring based on soil test recommendations for a 4.57 Mg seed ha^{-1} pea grain crop. To avoid negative effects of fertilizer applications on seedling emergence, up to 118 kg ha^{-1} fertilizer was side-banded 2.5 cm from the seed row. If fertilizer recommendations exceeded this, the remaining fertilizer was broadcast and incorporated with harrows.

Prior to seeding in 2004, triallate [S-(2,3,3-trichloroallyl)diisopropylthiocarbamate] at 1.7 kg ai ha^{-1} was applied and appropriately incorporated to control wild oats. After crop emergence, broadleaf weeds in faba bean, pea, and barley plots were controlled with an application of bentazon [3-(1-methylethyl)-(1H)-2,1,3-benzothiadiazin-4(3H)-one 2,2-dioxide] at 1.1 kg ai ha^{-1} in 240 L ha^{-1} of water at 275 kPa when the grain legumes were at the 3 to 4 node stage. In 2005, broadleaf weeds were controlled with two applications, 10 days apart, of metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one] at 138 g ai ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa. Wild oats were controlled with an application of tralkoxydim (2-

[1-(ethoxyimino)propyl]-3-hydroxy-5-(2,4,6-trimethylphenyl)-cyclohex-2-enone) at 198 g ai ha^{-1} with a water volume of 240 L ha^{-1} at 275 kPa three to five days after the first metribuzin application. In both years, any subsequent weed flushes were hand-weeded.

Straw yields were measured when each species reached physiological maturity. A 0.4-m^2 quadrat was hand-cut from each plot, at a height of 5 cm above the soil surface. Grain legume pods and barley heads were removed from the plants to simulate grain harvest. The pods, heads, and straw materials were dried at 40°C and weighed. Pods and heads were then threshed and seeds were weighed. Chaff yields were determined by subtracting seed weights from unthreshed pod and head weights. Straw material was weighed to determine straw yields.

After straw samples were collected, the crop was desiccated using diquat (6,7-dihydrodipyrido[1,2-a:2',1'-*c*]pyrazinediium ion) at 360 g ai ha^{-1} and a non-ionic surfactant at 0.24 L ha^{-1} in 240 L ha^{-1} of water at 275 kPa. When dry down was complete, plots were harvested with a Wintersteiger plot combine. The harvested seed was dried at 40°C and weighed to determine crop yields. To avoid straw mixing between adjacent plots over winter, all straw residues were collected directly from the combine and removed from the field. This simulated straw baling. As a result, N available to the subsequent wheat crop arose from decomposing root material, prior root exudates, and decomposing stubble (plant material remaining below the 5cm cutting height of the combine).

First year crop pot experiment

A pot experiment was conducted in 2005 to determine root biomass production of first year crops. Barley, faba bean, lupin, and pea were sown 5 May 2005 in 0.33 m x 0.22 m x 0.22 m (18.5 L) tubs to meet target plant densities used in the field experiment. Grain legume species were inoculated as in the field experiment. The potting media was a 20:20:60 mixture of sterilized soil:turface:sand, designed for easy removal of roots from the potting media. Prior to seeding, Nutricote total 13-13-13 controlled release fertilizer (Arysta Life Sciences North America, Cary, NC) was mixed with the potting media at a rate of 8 kg m^{-3}. Pots were placed outside, in wind shelters, and watered as necessary. At physiological maturity, aboveground plant parts were harvested and pods and barley heads were removed from the plants to simulate grain harvest. Potting media was washed from roots by soaking the root/potting media mixture in a bucket of water for 5 to 10 min. Potting media aggregates were washed off root tissues with a jet of water. Roots were soaked a second time to remove additional potting media. Broken roots in all stages were caught on 0.5 mm sieves. All separated plant material was dried at 40°C and weighed to determine straw, grain, and root DM. To predict field root DM production root:straw DM ratios, from the pot experiment, were applied to the field straw+stubble DM production. The root:straw DM ratios from the pot experiment were 0.25:1, 0.30:1, 0.28:1, and 0.16:1 for barley, faba bean, lupin, and pea, respectively. It should be noted that root measurements are problematic as measurement techniques cannot recover the complete root system and measurements do not capture root turnover or rhizodeposition (Unkovich and Pate, 2000).

Second year crop field experiment

In the year following the grain legume (2005, 2006), 'AC Intrepid' wheat was seeded into all plots to meet a target plant population of 250 plants m^{-2} (Alberta Agriculture and Food, 2001). No N fertilizer was applied, but P, K, and S were applied with the seed, in the furrow to meet soil test recommendations. Weeds were controlled with thifensulfuron methyl (3-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)amino]carbonyl] amino]sulfonyl]-2-thiophenecarboxylic acid) at 9.9 g ai ha^{-1}, tribenuron methyl (2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl)methylamino] carbonyl]amino]sulfonyl]benzoic acid) at 4.9 g ai ha^{-1}, quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) at 50 g ai ha^{-1}, and fenoxaprop (2-[4-[(6-chloro-2-benzoxazolyl)oxy]phenoxy]propanoic acid) at 70 g ai ha^{-1} with a water volume of 120 L ha^{-1} at 275 kPa. Straw yields were measured, as described in the first year. Once the grain was mature, plots were harvested with a Wintersteiger plot combine. The harvested seed was dried at 40°C and weighed to determine grain yields.

Nitrogen analysis and N_2 fixation estimates

Dried grain legume, barley, and wheat, straw and seed samples were ground with a Wiley mill to 1 mm and then analyzed for N concentration. Nitrogen concentration was determined using a LECO N-analyzer (Model CN-2000, Leco Corp., St Joseph, MI). Due to difficulties in collecting individual chaff samples, chaff N concentration was assumed to be equal to straw N concentration; however, this assumption may underestimate chaff N accumulation (Jensen, 1986). Seed N accumulation was determined by multiplying the N concentration of the seed by the seed yield. Straw, stubble, chaff, and root N accumulation were calculated by the same method. Root:straw N ratios, from the pot experiment, were multiplied by the field straw N concentration to predict field root N concentration. Root:straw N ratios from the pot experiment were 1.76:1, 1.57:1, 1.61:1, and 2.05:1 for barley, faba bean, lupin, and pea, respectively. Root N concentrations from the pot experiment could not be directly applied to the field as pot straw N levels were lower than field straw N levels.

Symbiotic N fixation and %Ndfa (percent plant N derived from the atmosphere) were determined with the N difference method (classical difference method) based on the following formulas (Rennie, 1984):

$$N_{\text{fixed}}\ (\text{kg ha}^{-1}) = \text{N yield}_{\text{fixing system}}\ (\text{kg ha}^{-1}) - \text{N yield}_{\text{non-fixing system}}\ (\text{kg ha}^{-1})$$

$$\%Ndfa = ([N\ yield_{fixing\ system}\ (kg\ ha^{-1}) - N\ yield_{non\text{-}fixing\ system}\ (kg\ ha^{-1})] / N\ yield_{fixing\ system}) \times 100$$

where fixing system was the grain legume crop and the non-fixing system was the barley crop. Barley is commonly used as the non-fixing system in calculating pea, faba bean, and lupin N fixation (Armstrong et al., 1997; Khan et al., 2003; Soon and Arshad, 2004).

The ^{15}N natural abundance method was used to supplement the N difference method of calculating symbiotic N fixation in aboveground biomass. First year barley was used as a non-fixing reference plant. Aboveground plant samples were subject to further grinding by a ball mill and analyzed for natural ^{15}N abundance ($\delta\ ^{15}N$) as well as total N concentration. The natural ^{15}N abundance analysis was performed on an Isotope Ratio Mass Spectrometer (V.G. Isogas LTD, Aston Way, Middlewich Cheshire, CW10 0HT, United Kingdom) with a direct combustion prep system (Carlo Erba NA 1500 Strumentazione, Strada Rivoltana, 20090 Rodan Milan, Italy). The %Ndfa was determined as (Shearer and Kohl, 1986):

$$\%Ndfa = (\delta^{15}N_{reference\ plant} - \delta\ ^{15}N_{grain\ legume}) / (\delta\ ^{15}N_{reference\ plant} - B) \times 100$$

where $\delta\ ^{15}N$ was calculated as the weighted average of grain and straw materials. B-values of -0.60, -0.55, and -0.72 were used for faba bean, lupin, and pea, respectively (Knudsen et al., 2004).

The potential N benefit (N_{add}) of grain legumes to total soil N was estimated by the N balance that included aboveground and belowground plant N. The following formula was adapted from Evans et al. (2001):

$$N_{add} = N_{\text{fixed}} - N_{\text{export (harvested seed and/or straw and chaff)}}$$

Soil labile N

Soil samples were collected five times per cropping cycle (prior to seeding the grain legume, part way through the grain legume growing season, immediately after harvesting the grain legume, prior to seeding the wheat, and part way through the wheat growing season) from each plot at random. In 2004, soil samples (0–15 cm depth) were collected from the middle of two adjacent rows. In 2005 and 2006, soil samples (0–15 cm depth) were collected between individual plants within a row. Samples were stored at 4°C until analysis which was usually within a week.

The following N availability indicators were measured: extractable ammonium (NH_4–N) and nitrate (NO_3–N), DON, and MBN. Total labile N was defined as the sum of NH_4–N, NO_3–N, DON, and MBN. Samples were sieved with a 4 mm screen prior to analysis. Ammonium N and NO_3–N were extracted from samples using a 0.25*M* K_2SO_4 solution (5:1 extractant:dry soil weight) (Jenkinson et al., 2004). Nitrate N and ammonium N were determined using a Technicon-AutoAnalizer II (Technicon Industrial Systems,Tarrytown, NY).

Microbial biomass N was determined using the chloroform-fumigation extraction method as per Horwath and Paul (1994). A 24 h fumigation period was used. Total dissolved nitrogen (TDN) was determined using a Shimadzu-VCSN instrument (Mandel Scientific Co., ON, Canada). Dissolved organic nitrogen was calculated as DON = TDN - inorganic $N_{(NH4-N,\ NO3-N)}$. Microbial biomass N was calculated using MBN = $DON_{fumigated}$ - $DON_{unfumigated}$.

Data analysis

All data were tested for normality using PROC UNIVARIATE (SAS Institute 2003). The analysis indicated that log transformations ($\log_{10}(x+1)$) were necessary for stubble DM production, chaff DM production, root N accumulation, straw N accumulation, stubble N accumulation, chaff N accumulation, and wheat straw N concentration.

A preliminary ANOVA was performed to detect significant year x treatment differences using the MIXED procedure of SAS, where year was considered a fixed effect. Twenty seven dependent variables had non-significant year x treatment interactions. For three dependent variables, there were significant year x treatment interactions ($P<0.05$) but these were attributed to magnitude differences; therefore, an ANOVA was performed on all data combined across years. Analyses of variance were performed with the MIXED procedure of SAS (Littell et al., 2006), where year and block were considered random effects and crop was considered a fixed effect. Data was analyzed with the NOBOUND option of proc MIXED to get better control over Type I error and improve power when covariance parameter estimates of zero occurred in preliminary analyses (Littell et al., 2006). Means were separated by the Tukey-Kramer method when ANOVA indicated significant treatment effects. A significance level of $P \leq 0.05$ was used for all statistical tests.

Data transformations were necessary, to improve normality, for all soil labile N data in the 2004–2005 and 2005–2006 cropping cycles. Most data were log ($\log_{10}(x+1)$) transformed, but in the 2005–2006 cropping cycle, NO_3–N data was square root transformed ($(x+0.5)^{0.5}$) while the percent MBN of labile and percent NO_3–N of labile data were arcsin transformed (arcsin (x)). In a preliminary ANOVA, using the MIXED procedure of SAS (SAS Institute, 2003) where year was considered a fixed effect, there were significant year x treatment interactions for the soil labile N data. As a result, years were analyzed separately with a repeated measures ANOVA with the MIXED procedure of SAS (Littell et al., 2006). Block was considered a random effect while first year crop and sampling time were considered fixed effects.

RESULTS AND DISCUSSION

In 2004, 2005, and 2006 mean temperatures from 1 May to 31 Aug. were 12.8, 13.5, and 15.6°C, respectively. Mean temperatures were cooler than the 30-yr average of 13.7°C in 2004, near the 30-yr average in 2005, and warmer than the 30-yr average in 2006. The first year crops were grown under cooler or normal temperatures (2004, 2005) while one second year wheat crop was grown under normal temperatures (2005) and the other second year wheat crop was grown under warmer than normal temperatures (2006). Rainfall for 1 May to 31 Aug. was less than the 30yr average of 300 mm in 2004 (276 mm), 2005 (255 mm), and 2006 (206 mm). Overall, this study was conducted under drier than normal conditions.

The absence of year x crop species interactions, for the majority of measured parameters, indicated consistent trends between years. Consistent responses, under varying climatic conditions, indicate that our findings represent typical trends for grain legume and subsequent wheat crop performance on central Alberta soils that are classified as an Orthic Humic Gleysol (mesic Typic Endoaquoll) with a heavy clay texture.

First year DM production

First year DM production was significantly different depending on crop species (Table 5-1). Faba bean and lupin had higher total DM production compared to pea. In Australia, Armstrong et al. (1997) also reported greater lupin biomass production compared to pea, while Mayer et al. (2003) reported greater faba bean DM production compared to pea. Grain DM yields were typical of the area (Harker, 2001). Barley root DM production was somewhat greater than values reported by Izaurralde et al. (1990) in central Alberta, Canada. Pea root DM production was similar to values reported in central Alberta, Canada

(Izaurralde et al., 1990) but greater than those reported in northern Alberta, Canada (Soon and Arshad, 2002).

First year N accumulation

Nitrogen concentration and accumulation differed significantly depending on the crop species (Table 5-1). Lupin accumulated the most straw, stubble, and chaff N, while faba bean accumulated the most grain N. Between 36 and 41% of the total lupin and barley plant N was accounted for in the grain while 68% of faba bean and 61% of pea N was in the grain. Straw N accumulation was greater than values reported in Australia (Haynes et al., 1993) and in northern Alberta, Canada (Soon and Arshad, 2004). Grain N accumulation was also greater than values from Australia, but of similar ranking (Armstrong et al., 1997). Greater N accumulation may be attributed to our study being conducted on a high organic matter soil (54 to 114 g kg^{-1}) compared to other studies where soil organic matter levels [1.72 x soil organic C] were 45 g kg^{-1} (Haynes et al., 1993), 55 g kg^{-1} (Soon and Arshad, 2004), and 26 g kg^{-1} (Armstrong et al., 1997). Greater N release from organic matter mineralization at our experimental site may have provided larger amounts of N to growing crops.

Root N accumulation decreased in the order: lupin > barley = faba bean = pea (Table 5-1). Haynes et al. (1993) and Evans et al. (2001) indicated that lupin and faba bean have greater root N compared to pea while Izaurralde et al. (1992) reported greater pea root N compared to barley. Lupin and pea root N accumulation was similar to values reported by Evans et al. (2001) in Australia, while pea root N accumulation was similar to values reported by Izaurralde et al. (1992) in central Alberta, Canada. Barley root N accumulation was greater than values reported by Izaurralde et al. (1992). Root N values were greater than values reported by Haynes et al. (1993) in New Zealand, and Senaratne and Hardarson (1988) in Austria. Differences were likely attributed to different methodologies of measuring root N accumulation (Khan et al., 2002).

First year N inputs

Soil N uptake for barley was 227 kg N ha^{-1} (Table 5-2). Nitrogen from fixation was determined by the N difference method, using barley as a reference species to estimate soil N uptake of the three grain legume species. In both years of the study, a visual assessment of nodulation found all grain legume species had numerous, large, pink-red nodules, indicating active nitrogen fixation. Faba bean and lupin fixed between 2.7 and 3.3 times more N (211 and 255 kg N ha^{-1}, respectively), than pea (78 kg N ha^{-1}). In addition, faba bean and lupin derived more of their total N from fixation (48 and 53%Ndfa, respectively) compared to pea (24%Ndfa). Low pea N fixation and %Ndfa, compared to lupin and faba bean, has been reported by other authors (Unkovich et al., 1995; Sparrow et al., 1995). Relatively low %Ndfa values for all crops may be attributed to the methodology used in this study as it does not account for the possibility of lower soil N uptake by the grain legumes relative to the barley reference (Senaratne and Hardarson, 1988).

Unfortunately the natural abundance method could not accurately measure N fixation as the soil natural ^{15}N abundance (δ^{15}N), reflected in the barley reference crop, was only 1.26 ± 0.32 in 2004 and 2.24 ± 0.27 in 2005 (Table 5-3). Unkovich et al. (1994) suggests a minimum δ^{15}N of two for the reference crop with preferable concentrations up to six. The low soil natural ^{15}N abundance in 2004 and 2005, may be caused by cultivation, fertilization, or soil texture (Kundsen et al., 2004).

Although reliable estimates of %Ndfa could not be obtained from the natural ^{15}N abundance data, %Ndfa values (Table 5-3) were calculated to compare %Ndfa values obtained by the N difference method (Table 5-2). Averaged over all grain legume species, the natural ^{15}N abundance method gave 19%Ndfa while the N difference method produced 42%Ndfa. Although there were large differences in magnitude, the two techniques produced similar rankings for the crop species in 2004. In 2005, the natural ^{15}N abundance method gave 25, 33, and 23% Ndfa for faba bean, lupin, and pea, respectively while the N difference method gave 54, 56, and 40% Ndfa for faba bean, lupin, and pea, respectively (data not shown). Small rank differences may be attributed to the natural ^{15}N abundance method being based solely on aboveground material while the N difference method was based on above and belowground material.

First year N exports

Although faba bean and lupin had the highest N fixation, they also had the highest N export (Table 5-2). The majority of faba bean N export was attributed to grain harvest (68%) while 41% of lupin N was exported as grain but 43% was exported as straw and chaff. Pea had moderate rates of N export while barley had the lowest N export. Low rates of barley N export are attributed to low grain N concentrations.

This study is unique in that straw, chaff, and grain were harvested in yr1. This technique mimics the N contributions of a commercial farming operation where straw and chaff are baled and used for livestock consumption or biofuel production. Although this makes comparisons with other studies difficult, Soon and Arshad (2004), in northern Alberta, Canada, found that straw management (retained vs. removed) did not influence grain, straw yields, or N uptake of a subsequent cereal crop. Other authors have also reported that removal of yr1 straw residues has little affect on yr2 plant N nutrition in the short term (Bremer and van Kessel, 1992).

Measured second year DM production and N accumulation

Wheat straw N concentration, grain N concentration, and straw N accumulation did not differ among previous crop species (Table 5-4). There were significant differences among previous crop types for all other measured parameters. Measured wheat N accumulation on the four stubble types decreased in the order: pea stubble = lupin stubble ≥ faba bean stubble = barley stubble.

Wheat DM grain yields grown on pea, lupin, and faba bean stubble were similar (Table 5-4). Similar trends were observed in a Danish study (Jensen et al., 2004), conducted on loam soils, where barley grown on pea and lupin stubble had similar yields. However, when the Danish study was conducted on a sandy soil, barley grain yield was significantly higher on lupin stubble compared to pea stubble. Armstrong et al. (1997) found that wheat grain yields were 20% greater on lupin stubble compared to pea stubble in an Australian study conducted on an acidic clay loam. Improved lupin rotational benefits, compared to pea, on sandy soils and acidic clay loams may be related to the fact that lupin is more tolerant of acidic conditions compared with other legume species and lupin is also adapted to coarse textured (sandy) soils (Gladstones, 1970).

The grain and total N accumulation of wheat grown on barley stubble ranked significantly lower than wheat grown on pea or lupin stubble (Table 5-4) which is in agreement with the findings of Armstrong et al. (1997). Of the three grain legumes, wheat grown on faba bean stubble had the lowest DM and N accumulation; however, differences among the three grain legume species were not always significant. Surprisingly, wheat grown on faba bean and barley stubble had similar straw DM production, total DM production, grain N accumulation, and total N accumulation. In agreement with our findings, higher yields from cereals grown on pea stubble, as compared to faba bean stubble, have been reported by Maidl et al. (1996) but in contrast to our findings similar yields on pea and faba bean stubble were reported by Senaratne and Hardarson (1988) and Wright (1990b). Once again different trends may be related to different soil and environmental conditions.

Predicted second year N accumulation: Accounting method

The N_{add} values ($N_{fixed} - N_{export}$) predicted wheat N accumulation would decrease in the order: lupin stubble > barley stubble = faba bean stubble = pea stubble (Table 5-2). Differences in N_{add}, among crop species, did not predict N accumulation by the yr2 crop (Table 5-4). Superior wheat performance was expected on lupin stubble; however, superior wheat performance was also observed on pea stubble (Table 5-4). N_{add} values underestimated the residual N value of grain legume stubble relative to barley stubble.

According to N_{add} values, all species had a N deficit at the end of the first year, despite calculations accounting for belowground root N (Table 5-2), which concurs with Haynes et al. (1993). The faba bean and lupin deficits were attributed to high N export, the pea deficit was attributed to low N fixation, while the barley deficit was attributed to no N fixation and N export.

Predicted second year N accumulation: Soil labile N

The repeated measures ANOVA indicated that soil labile N, and its components (MBN, DON, NO_3–N, and NH_4–N) were generally unaffected by crop type (Fig. 5-1, 5-2, and 5-3). Therefore, soil labile N measurements predicted wheat N accumulation would be similar on all stubble types. Due to large differences in wheat N accumulation among stubble types, measurements of soil labile N were a poor predictor of N availability for plant uptake.

Although this finding was surprising, other Canadian studies have found that MBN, the dominant component of soil labile N (Fig. 5-3), did not differ prior to seeding a subsequent crop, between pea-wheat and wheat-wheat rotations (Stevenson and van Kessel, 1996) or that crop rotation accounted for less than 1% of MBN variation (Soon and Arshad, 2004).

Soil labile N was a poor predictor of plant available N; however, there were seasonal changes in soil labile N and its components (MBN, DON, NO_3–N, and NH_4–N) (Fig. 5-1, 5-2, and 5-3) indicating that soil labile N may store some N which arose from the previous crop. Soil labile N and most of its components decreased over the yr1 growing season (0 to 156 or 159 days from the first sampling) (Fig. 5-1 and 5-2). At the beginning of yr2 (362 or 364 days from the first sampling), there was a slight increase in soil labile N followed by a gradual decrease over the second growing season (Fig. 5-1e and 5-2e). In the 2004–2005 cropping cycle this pattern can be primarily attributed to changes in NO_3–N (Fig. 5-1c) while in the 2005–2006 cropping cycle this pattern can be attributed to changes in NO_3–N (Fig. 5-2c) and MBN (Fig. 5-2a). We can offer no explanation as to why lupin DON, at 156 days from the first sampling, is high compared to the other treatments (Fig. 5-2b). On average, NO_3–N and MBN, account for 24 and 67% of soil labile N, respectively (Fig. 5-3). Other authors reported a peak in soil MBN in the spring following the grain legume crop (Jensen, 1994; Stevenson and van Kessel, 1996). In the 2005–2006 cropping cycle, a small peak was observed in soil MBN (Fig. 5-2a) in the spring following the grain legume crop (362 or 364 days from the first sampling); however, it is not apparent in the 2004–2005 cropping cycle (Fig. 5-1a). We might have found a more substantial peak if we had incorporated straw residues, had more frequent sampling times, or conducted the study on a lower N or lower organic matter soil.

Based on seasonal changes in soil labile N in the 2004–2005 cropping cycle (Fig. 5-1e), averaged over all crop types, the first year crop took up 81 kg N ha^{-1} from the soil between day 0 and day 159. In the 2005–2006 cropping cycle (Fig. 5-2e), averaged over all crop types, the first year crop took up 12 kg N ha^{-1} from the soil between day 0 and day 156. This is substantially less than the 227 kg N ha^{-1} that was taken up from the soil by first year crops (Table 5-2). The same trends occurred with the wheat crop. Based on seasonal changes in soil labile N in the 2004–2005 cropping cycle (Fig. 5-1e), averaged over all stubble types, the wheat crop took up 10 kg N ha^{-1} between day 364 and day 464. In the 2005–2006 cropping cycle (Fig. 5-2e), averaged over all stubble types, wheat took up 17 kg N ha^{-1} between day 362 and day 455. Again, this is substantially less than the average wheat total N accumulation of 134 kg N ha^{-1} (Table 5-3), as estimated from plant N uptake.

Explanations for poor predictability

The question remains why differences in N accumulation by the yr2 crop, among the four stubble types, (Table 5-4) could not be explained by accounting methods or differences in soil labile N and its components (Fig. 5-1, 5-2, and 5-3). First, differences in soil MBN, the primary component of soil labile N, among crop rotations may only be apparent in long term studies (Moore et al., 2000). Second, soil microbes in our study may not have been N limited, therefore, N would not be mineralized from decomposing crop residues until the residues reach a critical N concentration (Janzen and Kucey, 1988) and readily available C may dictate microbial assimilation of N (Wagger et al., 1985). Third, N mineralized over the winter may have been lost to immobilization, denitrification, or leaching (Jensen, 1994). Fourth, non-N rotational benefits including: grain legume crop effects on soil water (Gan et al., 2003), interruption of pest cycles (Derksen et al., 2002; Krupinsky et al., 2002), increased P, K, and S availability (Bullock, 1992), ameliorated soil structure (Bullock, 1992; Karlen et al., 1994), and soil H_2 fertilization (Dong et al., 2003) may have enhance subsequent crop N uptake. Stevenson and van Kessel (1996) suggest that possible increased root growth may provide access to a greater soil volume. Fifth, differences in subsequent crop N accumulation may be related to differences in the quality and nature of the previous crop residue (Soon and Arshad, 2004). Last, although changes in MBN were not observed, there may have been changes in the species composition of the microbial community that could affect N availability to the subsequent crop (Lupwayi et al., 1998).

Role of N in subsequent crop performance

Historically, the rotational benefits of grain legume crops have focused on the notion of improved N availability to the subsequent crop (Stevenson and van Kessel, 1996). However, this study was unable to predict plant N availability based on N_{add} (accounting method) or measure changes in soil labile N that accounted for differences in N accumulation of a subsequent wheat crop.

Other studies conducted in the northern prairies have also found that N was unable to account for differences in subsequent crop performance. For example, in Saskatchewan, Canada, Wright (1990b) found N fertilizer was unable to bring subsequent crops yields on barley stubble up to the subsequent crop yield on grain legume stubble. Similarly, Stevenson and van Kessel (1996) reported that in Saskatchewan, Canada, additional soil N in a pea-wheat rotation explained only 8% of the seed yield increases. Walley et al. (2007) suggests that the scientific community does not understand the N contribution of grain legume crops to cropping systems and more work is needed to quantify the N credit of grain legume crops.

High wheat yields on pea stubble may be attributed to synchronous N release from decomposing pea residues with subsequent crop N demands and non-N rotational benefits of pea being greater than non-N rotational benefits of faba bean or lupin. Stevenson and van Kessel (1996) suggested that non-N rotational benefits may indirectly enhance N accumulation in a subsequent cereal crop. A further assessment of non-N rotational benefits and N release timing from decomposing pea, faba bean, and lupin residues is required.

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Table 5-1. Dry matter (DM) yields, N concentrations, and N accumulation for above and extrapolated belowground biomass of first year crops in 2004 and 2005 at Barrhead, AB.

	DM production						N concentration			N accumulation (DM * N concentration)				
Crop	Root†	Straw	Stubble	Chaff	Grain	Total	Root†	Straw	Grain	Root†	Straw	Stubble	Chaff	Grain
	kg ha^{-1}						g kg^{-1}			kg N ha^{-1}				
Barley	1470 b	5550 b	367 b	2010 b	4470 c	13 800 bc	25 b	14 b	18 d	37 b	78 b	5 b	26 b	81 c
Faba bean	1540 b	4910 b	225 c	1890 b	7120 a	15 690 ab	23 c	14 b	42 b	36 b	72 b	3 c	28 b	300 a
Lupin	2190 a	7180 a	650 a	4130 a	3640 d	17 790 a	30 a	19 a	56 a	65 a	133 a	12 a	74 a	198 b
Pea	750 c	4420 b	260 c	1280 b	5320 b	12 020 c	33 a	16 ab	35 c	24 b	70 b	4 bc	20 b	186 b
						ANOVA								
Source of variation														
Crop *F* test	***	***	***	***	***	**	***	***	***	***	***	***	***	***
SE‡ crop	165	504	0.2	0.4	204	898	1.7	1.0	0.7	0.4	0.4	0.3	0.5	10

Values within one column followed by the same letter are not significantly different at $P<0.05$ as determined by a Tukey-Kramer means separation test.

† Root DM and N values in the field were extrapolated from the pot experiment. See explanation in text.

‡ Standard error of the difference of two least-squares means. Standard errors have been backtransformed where necessary.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 5-2. Total plant N, N uptake from soil, N from fixation (N difference method), N derived from the atmosphere (Ndfa) (N difference method), harvest indices, N export, and N_{add} of first year crops in 2004 and 2005 at Barrhead, AB.

Crop	Total plant N	N uptake from soil	N from fix	Ndfa	DM Harvest index	N Harvest index	N export (seed N + straw N + chaff N)	N_{add} (N fix – N export)	N_{add} (w/ seed export only)
	kg N ha^{-1}			%			kg N ha^{-1}		
Barley	227 c	227	0 c	0 c	87 c	82 c	185 c	-185 b	-81 b
Faba bean	439 a	227†	211 a	48 a	89 b	91 a	400 a	-189 b	-89 b
Lupin	483 a	227†	255 a	53 a	84 d	84 b	405 a	-150 a	57 a
Pea	305 b	227†	78 b	24 b	92 a	91 a	277 b	-199 b	-109 b
					ANOVA				
Source of variation									
Crop *F* test	***	--	***	***	***	***	***	***	***
SE‡ crop	29		28	5	0.7	0.9	22	9	21

Values within one column followed by the same letter are not significantly different at P<0.05 as determined by a Tukey-Kramer means separation test.

† Soil N uptake for faba bean, lupin, and pea, was assumed to be equivalent to barley

‡ Standard error of the difference of two least-squares means. Standard errors have been backtransformed where necessary.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 5-3. Straw, grain, and weighted $\delta^{15}N$ values and calculated percent N derived from the atmosphere (%Ndfa) for barley, faba bean, lupin, and pea grown in 2004 and 2005 at Barrhead, AB. All values are means ± standard error of the mean.

	$\delta^{15}N$ values						%Ndfa†	
	Grain		Straw		Grain + Straw		Grain + Straw	
Crop	2004	2005	2004	2005	2004	2005	2004	2005
	‰						%	
Faba bean	1.81 ± 0.15	1.98 ± 0.16	-0.03 ± 0.08	0.81 ± 0.47	0.96 ± 0.04	1.54 ± 0.21	16	25
Lupin	1.85 ± 0.10	1.90 ± 0.17	0.62 ± 0.21	0.92 ± 0.18	0.97 ± 0.15	1.32 ± 0.16	19	33
Pea	1.90 ± 0.12	2.01 ± 0.03	0.74 ± 0.31	0.97 ± 0.33	1.28 ± 0.15	1.56 ± 0.15	0	23
Barley	1.81 ± 0.30	3.36 ± 0.23	0.92 ± 0.36	1.04 ± 0.51	1.26 ± 0.32	2.24 ± 0.27	--	--

† Calculated based on aboveground biomass only.

Table 5-4. Dry matter (DM) yields, N concentrations, and N accumulation for aboveground biomass of second year wheat crops in 2005 and 2006 at Barrhead, AB.

Previous Crop	DM production			N concentration		N accumulation (DM*N concentration)		
	Straw	Grain	Total	Straw	Grain	Straw	Grain	Total
	-------- kg ha^{-1} --------			------- g kg^{-1} -------		----------------- kg N ha^{-1} --------------		
Barley	3590 b	4400 b	7990 c	4.1	23.1	15	103 b	118 b
Faba bean	3650 b	5070 a	8720 bc	3.6	23.4	13	117 ab	130 ab
Lupin	4020 ab	5380 a	9390 ab	4.0	22.8	16	124 a	140 a
Pea	4260 a	5370 a	9630 a	4.0	24.5	17	132 a	149 a
				ANOVA				
Source of variation								
Crop *F* test	**	***	***	NS	NS	NS	**	**
SE† crop	195	199	279	0.02	0.6	0.1	7	7

Values within one column followed by the same letter are not significantly different at $P<0.05$ as determined by a Tukey-Kramer means separation test.

† Standard error of the difference of two least-squares means. Standard errors have been backtransformed where necessary.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

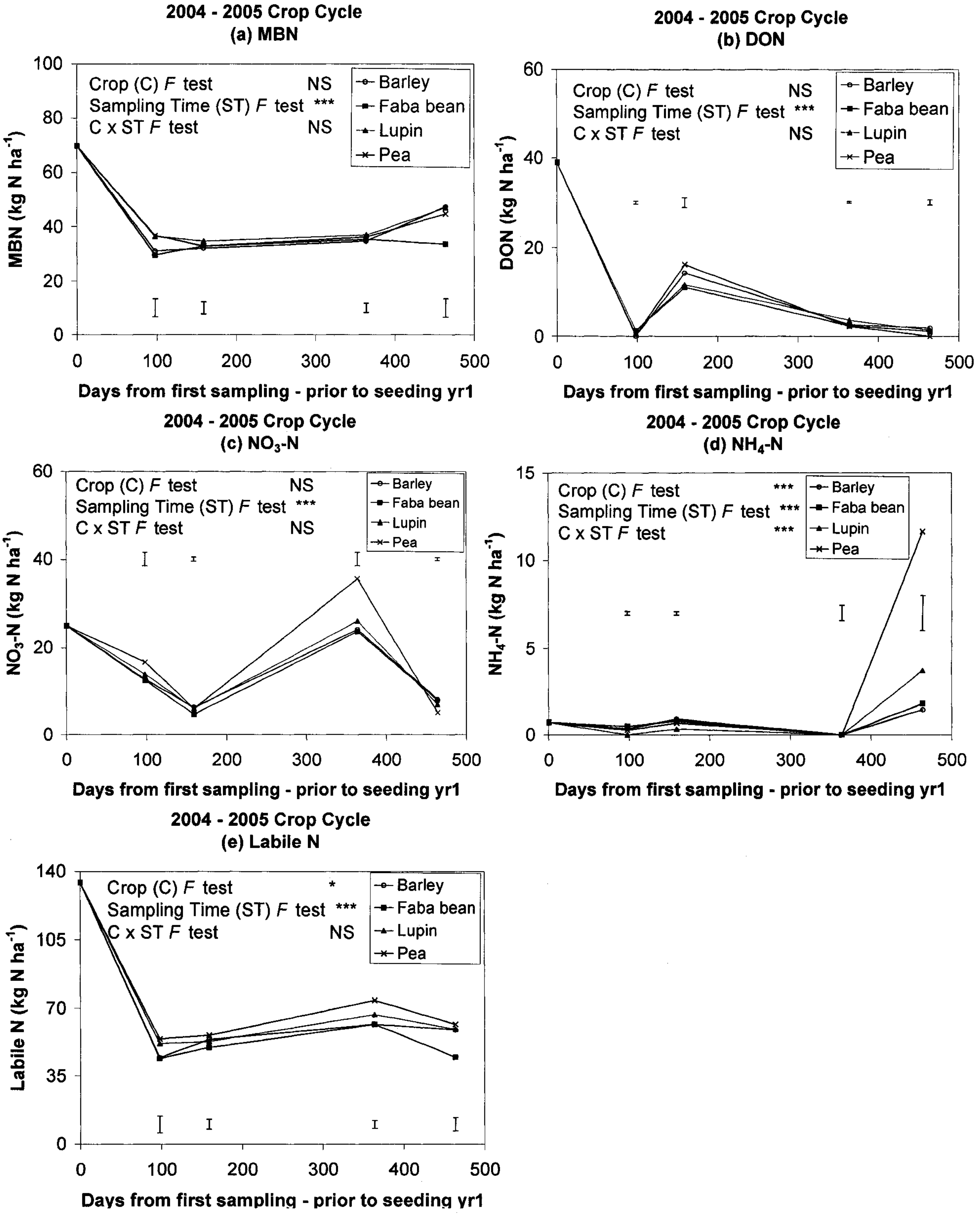
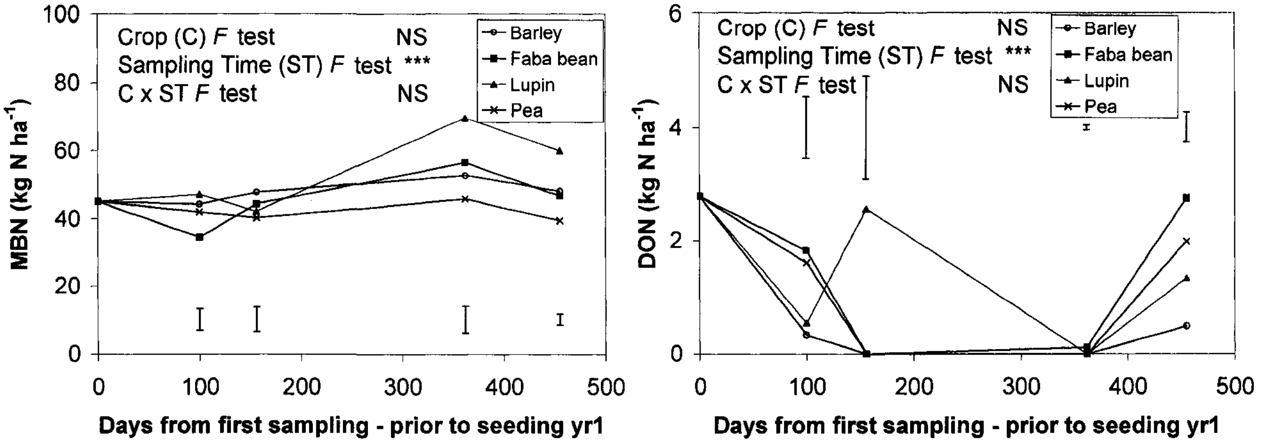
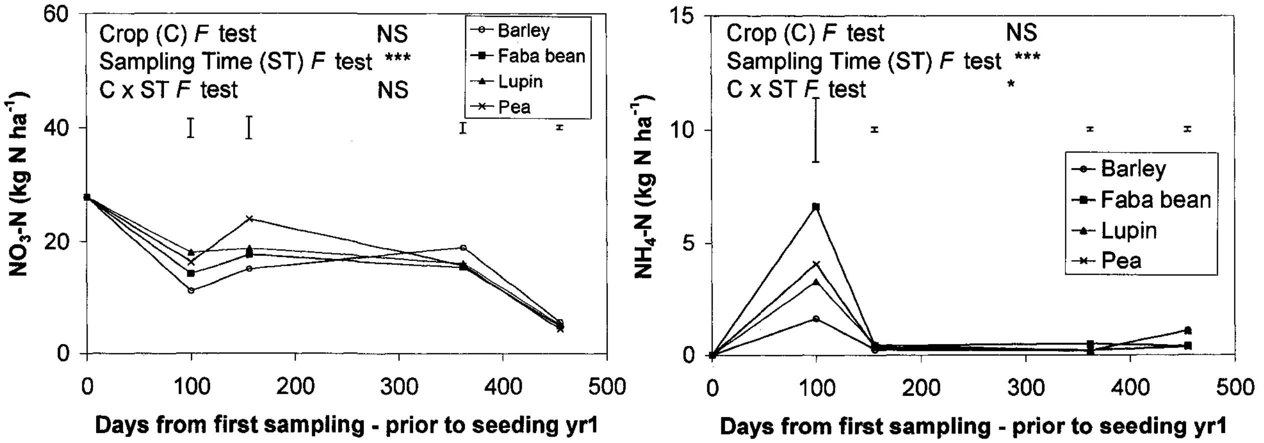


Fig. 5-1. Microbial biomass N (MBN), dissolved organic N (DON), NO3–N, NH4–N, and labile N (sum of MBN, DON, NO_3–N, NH_4–N) under barley, faba bean, lupin, and pea in 2004 and under their stubble in 2005, at Barrhead, AB. Sampling times correspond to yr1 crop seeding = 0 days from first sampling, yr1 silage harvest = 98 days from first sampling, yr1 grain harvest = 159 days from first sampling, yr2 wheat seeding = 364 days from first sampling, yr2 mid season = 464 days from first sampling. Bars indicate standard error of difference among the four crop types (n=16).



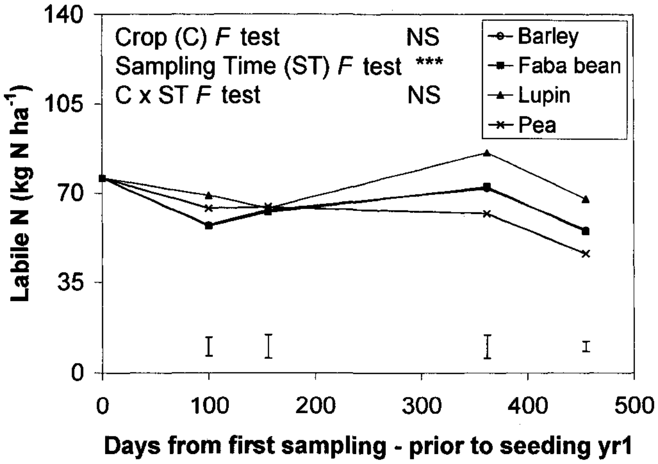
2005 - 2006 Crop Cycle
(a) MBN

2005 - 2006 Crop Cycle
(b) DON



2005 - 2006 Crop Cycle
(c) NO_3-N

2005 - 2006 Crop Cycle
(d) NH_4-N



2005 - 2006 Crop Cycle
(e) Labile N

Fig. 5-2. Microbial biomass N (MBN), dissolved organic N (DON), NO3–N, NH4–N, and labile N (sum of MBN, DON, NO_3–N, NH_4–N) under barley, faba bean, lupin, and pea in 2005 and under their stubble in 2006, at Barrhead, AB. Sampling times correspond to yr1 crop seeding = 0 days from first sampling, yr1 silage harvest = 100 days from first sampling, yr1 grain harvest = 156 days from first sampling, yr2 wheat seeding = 362 days from first sampling, yr2 mid season = 455 days from first sampling. Bars indicate standard error of difference among the four crop types (n=16).

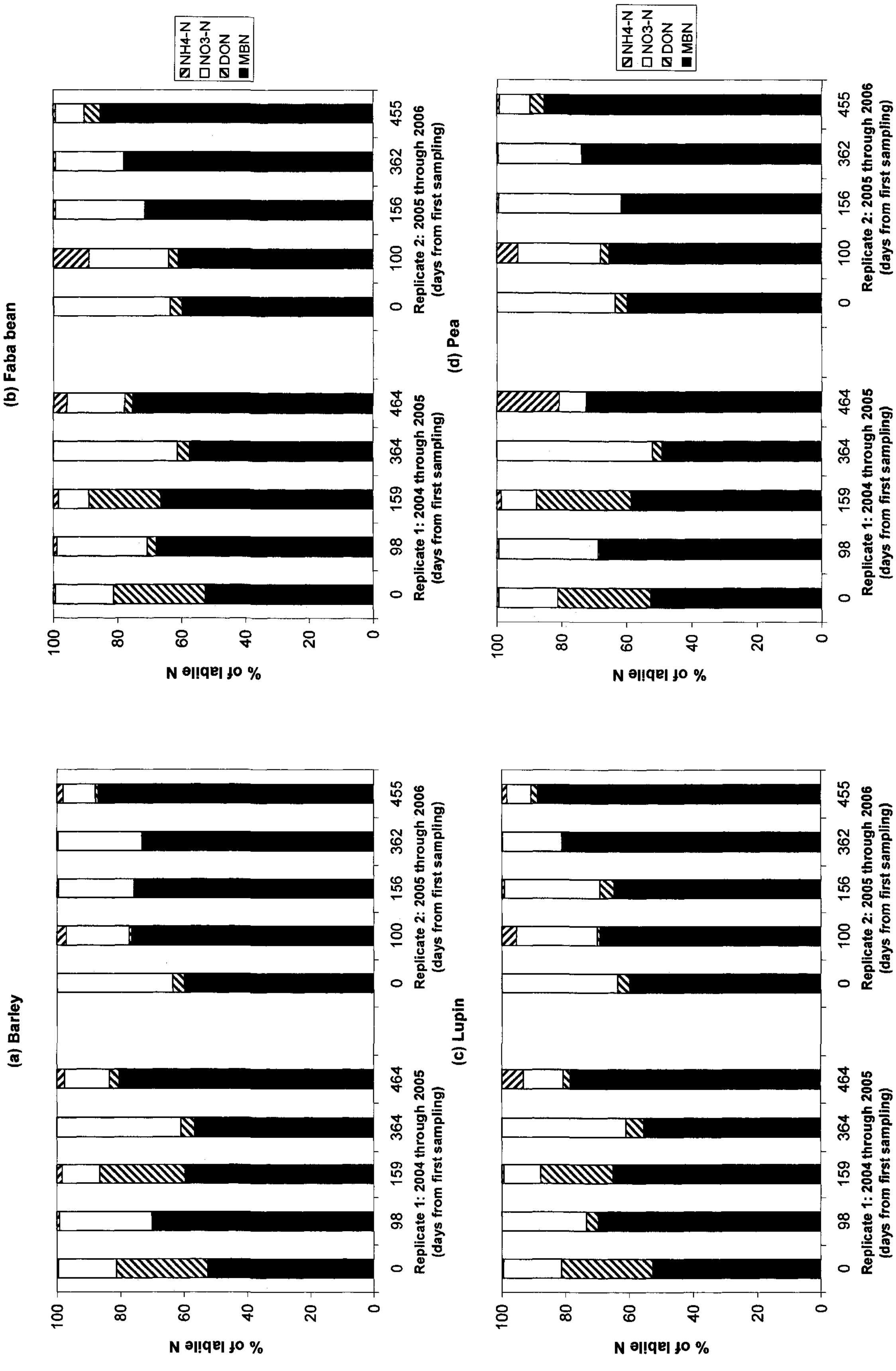

(a) Barley
(b) Faba bean
(c) Lupin
(d) Pea
% of labile N
100
80
60
40
20
0
0
98
159
364
464
0
100
156
362
455
Replicate 1: 2004 through 2005 (days from first sampling)
Replicate 2: 2005 through 2006 (days from first sampling)
▧ NH4-N
□ NO3-N
▨ DON
■ MBN

Figure 5-3

Fig. 5-3. NH_4–N, NO_3–N, dissolved organic N (DON), and microbial biomass N (MBN) as a percent of labile N for barley, faba bean, lupin, and pea planted soil at Barrhead, AB in the two replicated cropping cycles. All components of soil labile N are significantly affected by sampling time ($p<0.0001$). Percent NH_4–N in 2004 through 2005 is significantly affected by crop type ($p=0.0048$) and the crop type by sampling time interaction ($p<0.0001$). Percent NO_3–N in 2004 through 2005 is significantly affected by the crop type by sampling time interaction ($p=0.005$). Percent NH_4–N and % MBN in 2005 through 2006 are significantly affected by the crop type by sampling time interaction ($p=0.03$ and $p=0.04$, respectively). All other components of soil labile N are not significantly affected by crop type or the crop type by sampling time interaction. Days from first sampling correspond to major cropping events in replicate 1 and 2. Yr1 crop seeding = 0 days from first sampling, yr1 silage harvest = 98 or 100 days from first sampling, yr1 grain harvest = 159 or 156 days from first sampling, yr2 wheat seeding = 364 or 362 days from first sampling, yr2 mid season = 464 or 455 days from first sampling.

Chapter 6

Summary and Synthesis

Chapter 6

Summary and Synthesis

Traditionally, field pea has been the only pulse crop grown in the Parkland region of Alberta. Recently, tannin free faba bean and narrow leaf lupin have shown potential as new pulse crops for the region. There was a need to establish local basic best management practices, for these new crops, to quantify their productivity, to determine their contributions to Alberta cropping systems, and to assess their role in improving the rotational benefits of Alberta cropping systems. The findings of this study will allow the pulse industry to increase and diversify pulse acres in the Parkland region of Alberta, based on:

- The availability of tested, local production practices (seeding rates and weed interference) for faba bean and lupin.
- High quality and economically feasible forage production from pea-barley intercrops which can be produced without N fertilizer and its associated environmental risks.
- Faba bean having an 18% higher seed yield potential compared to pea, in higher moisture environments.
- Lupin and faba bean having estimated N fixation rates double that of field pea.

- The potential for decomposing pea, faba bean, and lupin crop residues to supply 45%, 71%, and 125%, respectively, of subsequent wheat crop's N needs.
- A 15 to 22% yield increase in wheat grown on pulse stubble compared to barley stubble.
- An increase in grain N content, up to 6%, for wheat grown on pulse stubble compared to barley stubble.

I identified basic best management practices for new pulse crops, compared to pea, which optimized production, N fixation, and subsequent wheat crop yield and quality (Chapter 3). Pulse crops seeded with barley, as a model weed, demonstrated potential as annual forage intercrops, that could be grown without N fertilizer, and this led to assessing forage yield and quality parameters of pulse-barley mixtures (Chapter 2). The potential N rotational benefits, of the three pulse crop species, were compared by examining N release from decomposing crop residues (Chapter 4). The fate of biologically fixed N was followed from the pulse crop, to the soil labile N pool, and to a subsequent wheat crop in an attempt to more fully quantify long term N rotational benefits of pea, faba bean, and lupin (Chapter 5).

The research in this thesis was conducted to the best of my ability given the available resources. However, the following deficiencies should be acknowledged as an indication of sound science.

- There are still some constraints to lupin being adopted as an economically viable crop in Alberta. Future research should focus on increasing crop yield, improving competitive ability, and registration of suitable herbicides.
- Nitrogen fixation values reported in this thesis (Chapters 3 and 5) are dependent on the method used to measure N fixation (N difference method) and the reference species (barley) used to estimate soil N uptake.
- Allowing litterbags to decompose in an area planted with a subsequent crop would have altered the soil surface microclimate (reduced temperature and moisture variations) and may have increased decomposition rates of surface placed residues. Also, rhizodeposition from the live plant material might have resulted in larger soil microbial communities thus altering the soil nutrient dynamics and influencing decomposition rates of buried residues.
- In many Alberta cropping systems straw, stubble, chaff and root tissues remain in the field after harvest. I only examined N release from straw tissues (Chapter 4), which represent 51-66% of the residues retuned to the soil in a typical cropping system. Thus my results likely underestimate the potential nutrient supplying ability of crop residues.
- The accuracy and predictive ability of the N budget (Chapter 5) could have been improved if I had been able to measure N loss through leaching, root turnover, and rhizodeposition, and if soil samples were taken to greater depth.

- In this study, rotational benefits were assessed where straw from first year crops was removed from the field simulating straw baling (Chapters 3 and 5). Straw removal represents a significant source of N export from the field, and may have reduced the performance of the subsequent wheat crop.

OBJECTIVES

The objectives of the research conducted in this thesis were:

1. To determine if pulse crop management practices can affect the productivity of a subsequent wheat crop. (Chapter 3: Weed Interference, Pulse Species, and Plant Density Effects on Rotational Benefits)
2. To determine the feasibility of faba bean-barley, lupin-barley, and pea–barley intercrops for forage production in the Parkland region of Alberta, Canada. (Chapter 2: Forage potential of intercropping barley with faba bean, lupin, or field pea)
3. To quantify the role different pulse crops and reduced tillage can play in supplying N to subsequent crops. (Chapter 4: Long-term N release from faba bean, lupin, pea, and barley crop residues)
4. To obtain a quantitative measure of the effects tannin free faba bean, narrow leafed lupin, field pea, and barley have on Alberta soil fertility and a subsequent wheat crop's N accumulation. (Chapter 5: The role of N cycling in grain legume-wheat cropping sequences)

SUMMARY OF FINDINGS

	Tannin Free Faba Bean	Narrow Leafed Lupin	Field Pea
Maximum seed yield	7,640 kg ha^{-1}	4,020 kg ha^{-1}	6,460 kg ha^{-1}
Yield potential	Highest seed yields in higher rainfall environments (466 to 563 mm), indicating their high moisture requirements	Lupin had the lowest seed yields	Highest seed yields in growing environments with lower annual precipitation (346 to 366 mm)
Effects of pulse planting density on seed yield	Maximum yields were achieved with 1.5x or 2.0x the recommended planting density. The recommended planting density should be increased from 45 to 68 plants m^{-2}	Maximum yields were achieved with 1.5x the recommended planting density. Due to poor lupin emergence (76% of expected) this corresponded to 114 plants m^{-2}	Maximum yields were achieved with 1.0x (75 plants m^{-2}) or 1.5x (113 plants m^{-2}) the recommended planting density
Effects of grassy weed pressure on seed yield	Grassy weeds reduced seed yields by 42%	Grassy weeds reduced seed yields by 67%. For lupin to be a practical option for Alberta producers, lupin seed must have a higher market value than pea or faba bean to compensate for lower yields and higher weed control costs	Grassy weeds reduced seed yields by 27%. Pea seed yields were least affected by weed pressure, indicating that pea is the most competitive of the three pulse species
Forage yields in mixtures with barley	DM yields were lower than pea-barley or barley sole crop	Low yielding, due to the poor competitive ability of lupin in mixture with barley	Yields were comparable to sole barley. Pea was the most suitable species for intercropping with barley
Forage quality in mixtures with barley	Highest crude protein content and protein yield	Low quality due to low proportion of lupin in total dry matter	Forage quality was improved relative to sole barley
N fixation yields (in the absence of weed interference)	Highest N fixation yields which ranged from 70 to 223 kg N ha^{-1}	Moderate N fixation yields which ranged from 46 to 173 kg N ha^{-1}	Lowest N fixation yields which ranged from 78 to 147 kg N ha^{-1}

	Tannin Free Faba Bean	**Narrow Leafed Lupin**	**Field Pea**
Effects of weed pressure on N fixation	N fixation was reduced by 39% in the presence of weed pressure	N fixation was reduced by 70% in the presence of weed pressure	N fixation was slightly reduced in the presence of weed pressure, but the difference was not significant
%Ndfa	54% of total plant N was from fixation	43% of total plant N was from fixation	49% of total plant N was from fixation
N release from crop residues, at the time of peak subsequent crop demand	surface placed and buried residues released 63 and 72 kg N ha^{-1}, respectively	surface placed and buried residues released 106 and 131 kg N ha^{-1}, respectively	surface placed and buried residues released 37 and 49 kg N ha^{-1}, respectively
Potential N supplying power of decomposing residues	faba bean residues could potentially supply 71% of a subsequent wheat crop's N needs	lupin residues could potentially supply 125% of a subsequent wheat crop's N needs	pea residues could potentially supply 45% of a subsequent wheat crop's N needs
Subsequent wheat crop yield (averaged over all sites and management practices)	4,500 kg seed ha^{-1}	4,120 kg seed ha^{-1}	4,610 kg seed ha^{-1}
Subsequent wheat crop yield on weed free stubble (mean of Barrhead 2005 and 2006)	5,070 kg seed ha^{-1}	5,376 kg seed ha^{-1}	5,370 kg seed ha^{-1}
Seed and straw N exports following pulse harvest	greatest N exports (372 kg N ha^{-1})	moderate N exports (331 kg N ha^{-1})	lowest N exports (257 kg N ha^{-1})
N deficit or credit following the pulse crop	-152 kg N ha^{-1}	-121 kg N ha^{-1}	-158 kg N ha^{-1}

CONTRIBUTION TO KNOWLEDGE

The research I conducted provides local production knowledge for tannin free faba bean and narrow leafed lupin in the Parkland region of Alberta. On a broader scale, my research addressed a number of topics which have received little attention from the scientific community but are critical to understanding the mechanisms of pulse rotational benefits. There have been very few studies which compared faba bean, lupin, and pea agronomy or cropping systems. Canadian and European studies commonly compare pea and faba bean while Australian studies typically compare pea and lupin.

Development of Production Practices for Specific Regions

In the Parkland region of Alberta, the recommended planting density of tannin free faba bean needs to increase from 43 plants m^{-2} to 68 plants m^{-2}, in order to optimize yield, particularly when weed interference is present. However, the Australian recommended lupin planting density of 100 plants m^{-2} was sufficient for Alberta production (Chapter 3). Weed control was critical for faba bean and lupin crops, as grassy weeds can reduce seed yields by 42% and 66%, respectively. To compensate for lower lupin yield potential and higher weed control costs, lupin seed must have a higher market value (or greater rotational value) than pea or faba bean.

Investigating the Role of Pulse Crop Management on Subsequent Wheat Crop Performance

Many studies have examined production practices which optimize N fixation but few studies have investigated the effects of production practices on subsequent crop performance (Chapter 3). I examined the effect of weed competition and pulse planting density on pulse crop performance, N fixation, and subsequent wheat crop performance. I found that management practices (absence of weed pressure and increased seeding rate) which significantly improved pulse crop performance and N fixation, led to only small improvements in subsequent wheat crop performance, suggesting that maximizing pulse production does not markedly increase the rotational benefits to the subsequent wheat crop.

Developing Intercropping Recommendations that Consistently Result in Improved Forage Quality

Previous research has studied pulse-cereal forage intercrops that were heavily dominated by the cereal species and only occasionally did these studies report improved yield and quality. By using a low target barley planting density (53 plants m^{-2}), I created pulse-barley intercrops that were not dominated by the cereal species and this resulted in consistent improvements in forage nutrient values (Chapter 2). By increasing the pulse planting density, from 0.5x to 2.0x's the recommended monoculture planting density, I consistently increased the proportion of pulse in the forage dry matter and the CP concentration. These intercrops offer the opportunity to produce annual forage with comparable nutritive value to perennial alfalfa.

Investigating Long Term Decomposition of Crop Residues

The decomposition of agricultural crop residues has rarely been studied beyond 12 months (Chapter 4). To address the dynamic, long term nature of residue decomposition, I monitored the rate and extent of pulse crop residue decomposition over a 22-month period. During this time, I observed rapid decomposition of buried residues which supports the hypothesized decomposition pattern of Lupwayi et al. (2004) for residues decomposing in conventional tillage systems. In my study, surface placed residues experienced relatively faster rates of decomposition and N loss in the first 12 months of decomposition but slower decomposition and N loss in the latter 10 months of decomposition. This observation does not support Lupwayi's et al. (2004) hypothesis (of a second phase of rapid decomposition in the second year of decomposition) for crop residues in a zero-till system. However, I suggest that slow N release in no-till systems can be desirable, as there may be greater opportunity for N uptake over the long term.

Assessing the N Supplying Power of Decomposing Pulse Crop Residues

I found that tannin-free faba bean and narrow-leafed lupin crop residues have the potential to supply more N to subsequent crops compared to pea crop residues (Chapter 4). However, the timing of N release from decomposing lupin and faba bean crop residues did not coincide well with the timing of subsequent crop N uptake. Despite the low N supplying potential of pea residues, superior subsequent wheat crop performance on pea stubble (Chapter 3 and 5) may be attributed to better N synchrony.

Accounting for the N Contribution of Root Materials to Cropping Systems

Due to the difficulty of assessing root growth in the field, few studies have complied N budgets for pulse-cereal cropping systems which include belowground N (Chapter 5). My experiment estimates that root N accounted for 4 to 10% of total crop N. Although these root N values were lower than values reported in Australian studies (Evans et al. 2001), their inclusion in the N budget improved accuracy and these values may reflect lower belowground N accumulation in the Canadian prairies compared to Australia.

Evidence that Pulse Rotational Benefits are Not Primarily Attributed to Increased N Availability

Wheat grown on different stubble types accumulated different amounts of grain and total plant N (Chapter 5). My objective was to establish the N source which explained differences in N uptake. Soil microbial biomass did not differ under pea-wheat, faba bean-wheat, lupin-wheat, and barley-wheat cropping sequences. This led me to investigate soil labile N (microbial N, NO_3^-, NH_4^+, and dissolved organic N). However, there were no differences in soil labile N among the four cropping sequences that explained differences in subsequent wheat crop

N uptake. My study contributed to the growing body of evidence, which indicates the increased yield and quality of crops grown on pulse stubble cannot be primarily explained by changes in soil N availability (Walley et al. 2007).

FUTURE RESEARCH NEEDS

Improving the Accuracy of N Fixation Measurements

Accurate N fixation measurements depend on the non-fixing reference crop taking up the same amount of soil N as the N fixing crop. Different soil N uptake by the non-fixing reference crop, compared with the N fixing crop, will over or underestimate N fixation. To address this, future studies should use multiple reference crops, such as canola or nearby weed species, when quantifying N fixation. As there are problems with all methods of measuring N fixation, I would also advocate the use of multiple measurement techniques (^{15}N isotope dilution method, ^{15}N natural abundance, and N difference method).

Non-N Pulse Benefits

I was unable to explain differences in subsequent wheat crop yield based on the N budget or soil labile N (Chapter 5). There is thus a need to further investigate other pools of soil N (such as recalcitrant N and total N), and N losses. A thorough assessment of potential non-N benefits such as reduced root and leaf diseases, reduced weed pressure in the subsequent crop, possible changes in P, K, and S availability, improved soil structure, and release of growth substances from the pulse residue (Stevenson and van Kessel 1996) may also help to explain subsequent crop yield differences.

Rotational studies conducted in the dry semiarid northern Great Plains (30-yr average annual precipitation 349 mm) have found that additional soil moisture following the pulse crop accounts for much of the non-N rotational benefit (Miller et al. 2002). The non-N rotational benefit of post harvest soil moisture needs to be assessed in the Parkland region of Alberta where the 30-yr average annual precipitation ranges from 446 to 510 mm (Appendix 1-4, 1-5, 1-6).

Pulse Production Benefits on Low N Soils

It would be valuable to test N fixation potential and subsequent crop performance on soils with low available N levels and low organic matter contents. The high N content of unfertilized barley, and relatively low pulse %Ndfa (43 to 54%), suggest that N fixation was not optimized in my study. As a result, some pulse N benefits may have been masked by mineralization of soil organic matter. It should be noted that although N fixation is generally reduced on high N soils, the soils used in this study represent the Parkland region of Alberta, where faba bean, pea, and lupin are best suited for growth.

Pulse Production Benefits Compared to Cereals Grown with N Fertilizer

In order to determine N fixation by the N difference method, I grew a barley crop which did not receive N fertilizer. In three of the four studies, I compared pulse performance to this barley crop (Chapter 2, 4, and 5). It would be worthwhile for future studies to compare pulse performance with a barley crop receiving N fertilizer.

Pulse Rotational Benefits of Pulse-Barley Intercrops Harvested for Forage

I have shown that high quality, high yielding, economically feasible pulse-barley silage can be grown without the use of N fertilizer (Chapter 2). Pulse-barley intercrops offer the opportunity to greatly reduce farmer's N fertilizer use, and its associated environmental risks. However, an investigation of the rotational benefits to a subsequent crop grown on intercrop forage stubble would further help to quantify rotation benefits in this system.

Adjusting Legume Planting Density for Custom Forage Nutrition

In Chapter 2, I have shown that the forage nutritional quality changes based on the legume planting density in the mixture. A preliminary assessment of the nutritional quality of each component (the barley and the grain legume) suggests that forage quality of the mixture is the result of two factors: (i) the blending of different proportions of high (grain legume) and low (barley) quality plant material, and (ii) different nutritional quality of each component depending on the legume planting density. This information could be used to grow grain legume-barley intercrops using specified legume planting densities to achieve a desired forage nutritive value.

Pulse Root Production in the Field

The findings of my study (Chapter 5) and others conducted in this growing environment (Izaurralde et al. 1990, Soon and Arshad 2002) indicated a wide range of root DM production. Field assessments of belowground root N and rhizodeposition are necessary to establish more accurate N budgets and to quantify pulse N rotational benefits. Future research should focus on sequential measurements of root growth and soil NO_3-N and NH_4-N. This will help to establish the environmental credit of pulse crops to northern prairie cropping systems by quantifying pulse crop N inputs, accurately measuring the soil labile N pool, and documenting non-N benefits in the most common crops grown in northern prairie cropping systems.

Identifying Optimum Pulse Based Cropping Sequences

In this thesis I investigated the rotational benefits in pulse-wheat cropping sequences. However, subsequent crop species may well differ in their ability to capture pulse rotational benefits. In order to identify the most favorable cropping sequences, it is important that the most responsive species be identified by concurrently studying a range of subsequent crops.

CONCLUSION

I have established local production practices for tannin-free faba bean and narrow-leafed lupin in the Parkland region of Alberta. Tannin-free faba bean was found to have higher yields (in moister growing environments) and twice as much N fixation compared to pea, the traditional pulse crop in the region. Distribution of this information to Alberta pulse growers should help increase and diversity pulse acreage.

Tannin-free faba bean, narrow-leafed lupin, and field pea are valuable additions to Alberta cropping systems. They require no N fertilizer in their production year and can produce high quality forage in mixtures with barley. Decomposing aboveground pulse crop residues have the potential to supply 45 to 125% of a subsequent wheat crop's needs. A complex interaction of pulse N and non-N rotational benefits contribute to a 15 to 22% increase in subsequent wheat crop yield. Increasing the use of pea, faba bean and lupin in cropping systems can increase species diversity, reduce N fertilizer inputs, and increase overall productivity of prairie agroecosystems.

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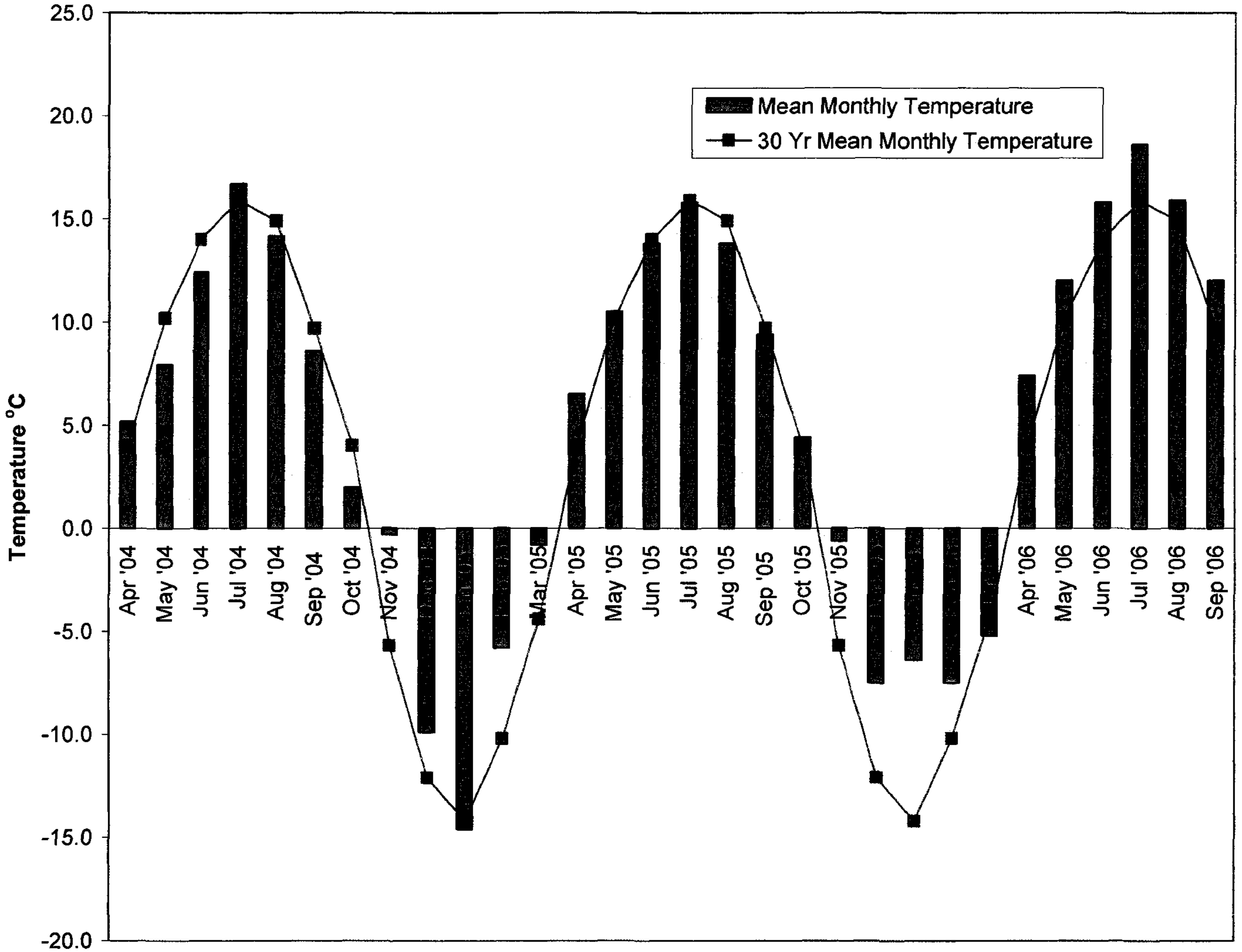
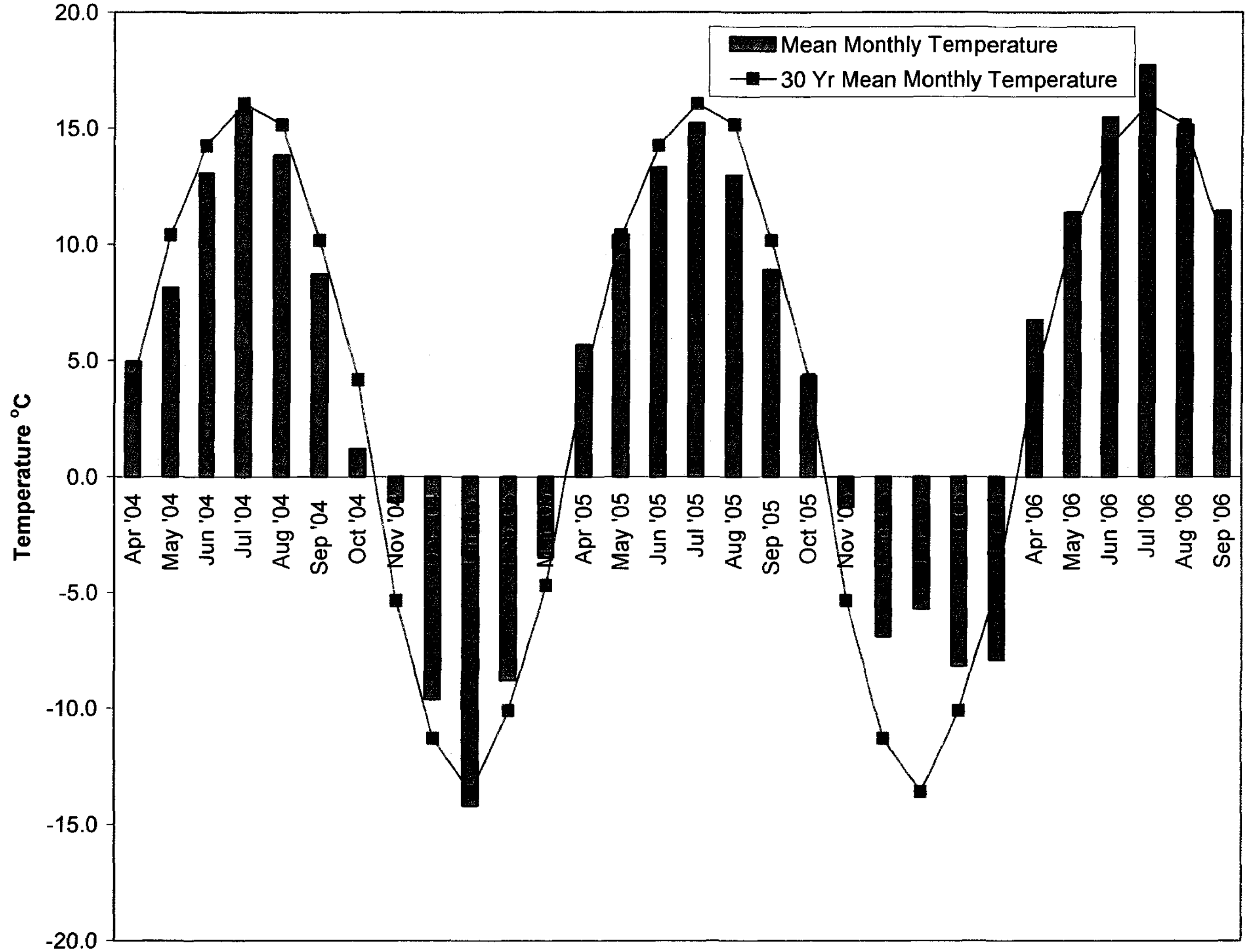
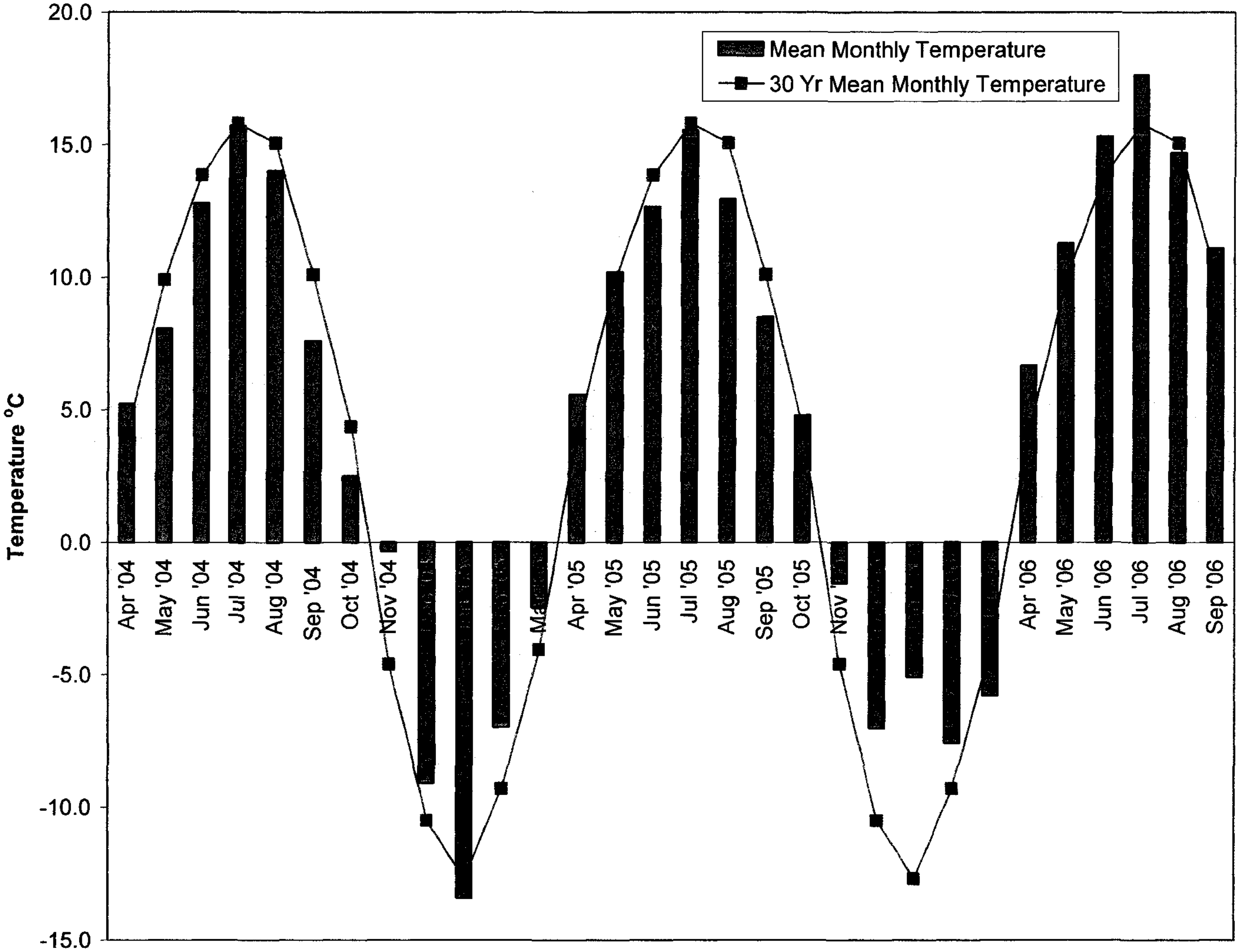
Appendix 1: Climate Data



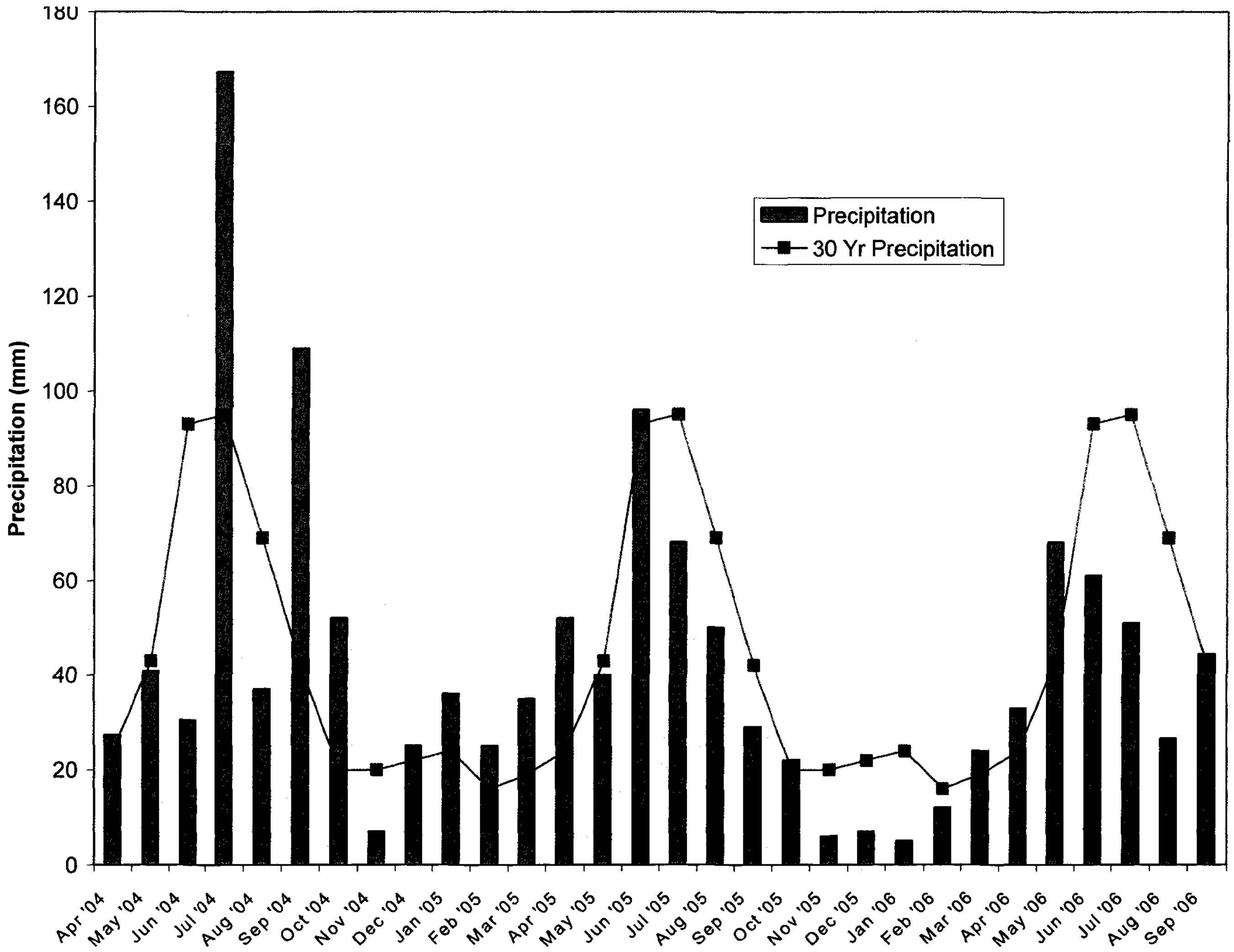
Appendix 1-1: Monthly mean temperatures from April 2004 to September 2006 and 30-yr average temperatures at Barrhead, AB, Canada.



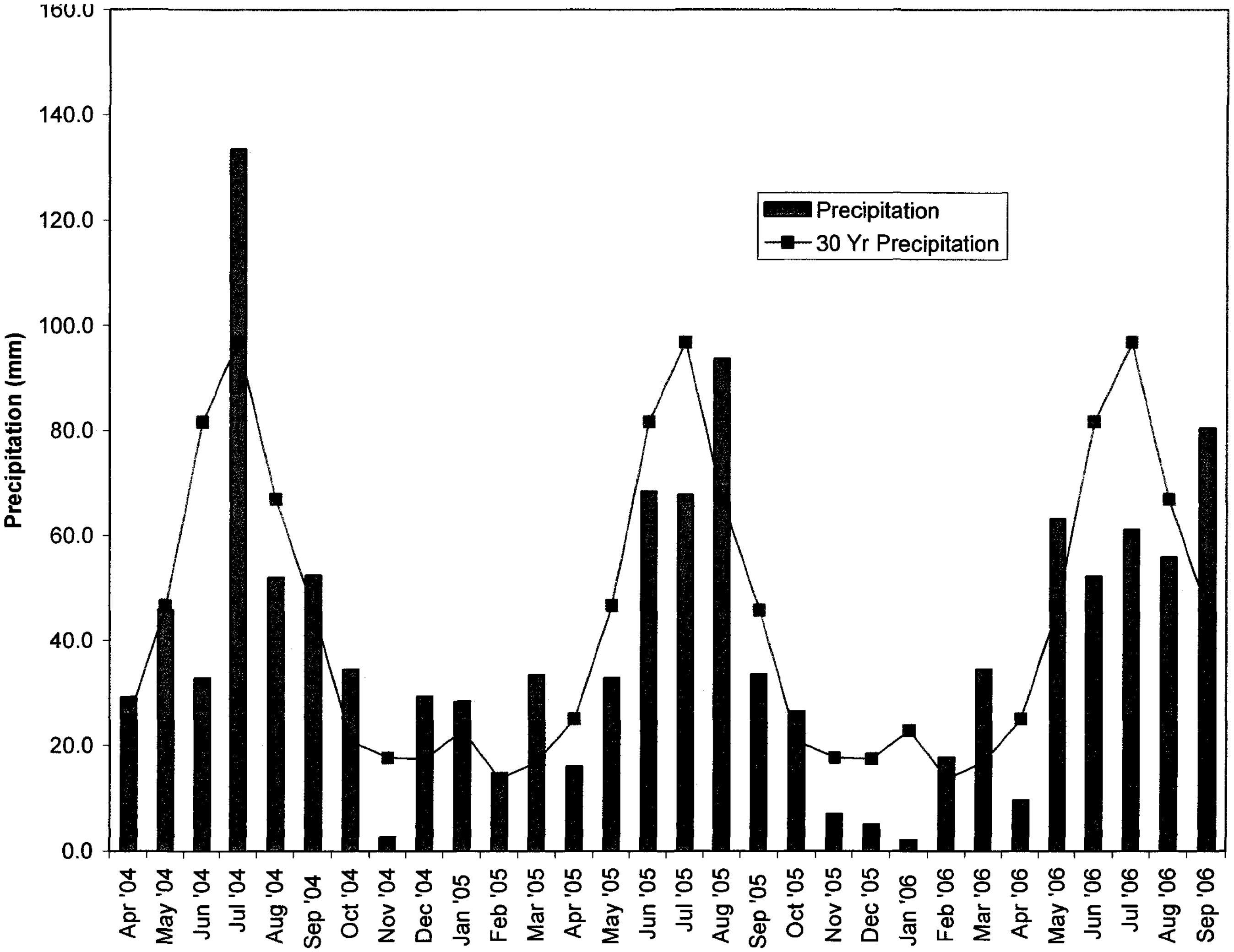
Appendix 1-2: Monthly mean temperatures from April 2004 to September 2006 and 30-yr average temperatures at Devon, AB, Canada.



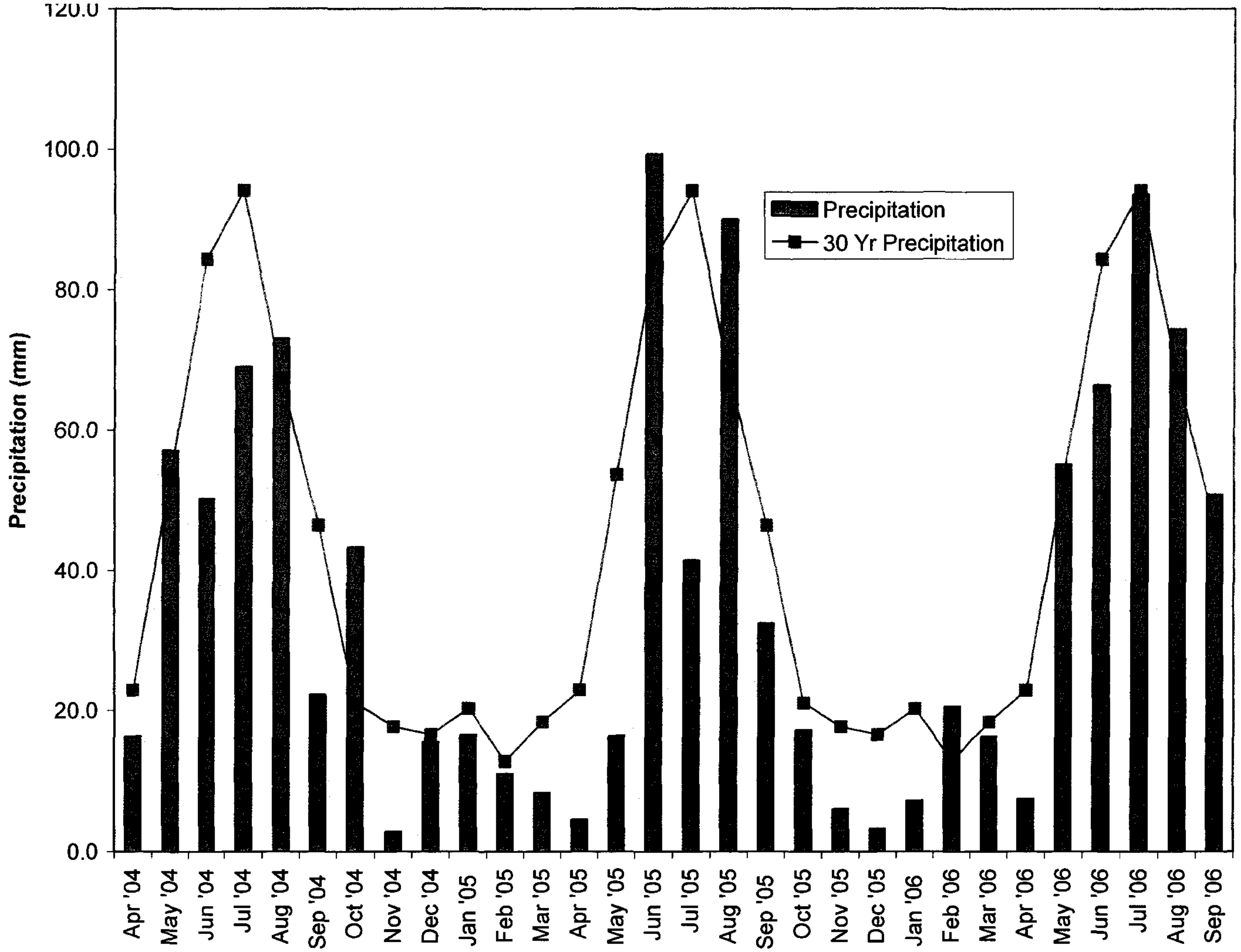
Appendix 1-3: Monthly mean temperatures from April 2004 to September 2006 and 30-yr average temperatures at Lacombe, AB, Canada.



Appendix 1-4: Monthly precipitation from April 2004 to September 2006 and 30-yr average monthly precipitation at Barrhead, AB, Canada.



Appendix 1-5: Monthly precipitation from April 2004 to September 2006 and 30-yr average monthly precipitation at Devon, AB, Canada.



Appendix 1-6: Monthly precipitation from April 2004 to September 2006 and 30-yr average monthly precipitation at Lacombe, AB, Canada.

Appendix 1-7: Target plant populations for first year barley, faba bean, lupin, and pea crops grown at Barrhead, Devon, and Lacombe, AB, in 2004 and 2005.

	Target plant populations			
PPD	Barley	Faba Bean	Lupin	Pea
	---------- plants m^{-2} ----------			
0.5x	n/a	23	50	38
1.0x	210	45	100	75
1.5x	n/a	68	150	113
2.0x	n/a	90	200	150

Appendix 1-8: Summary of treatment effects (Chapter 3) on pulse seed yield, aboveground N fixation, and %Ndfa at Barrhead, Devon, and Lacombe, AB in 2004 and 2005.

	Barrhead		Devon		Lacombe	
Treatment Effect	2004	2005	2004	2005	2004	2005
			Pulse seed yield			
Weed (W) *F* test	***	***	***	***	**	***
Species (S) *F* test	***	***	***	***	***	***
W x S *F* test	***	***	***	***	ns	***
PPD *F* test	***	***	***	***	***	***
W x PPD *F* test	***	***	***	***	ns	***
S x PPD *F* test	ns	**	ns	**	***	ns
W x S x PPD *F* test	ns	*	ns	ns	**	ns
			Aboveground N fixation			
Weed (W) *F* test	*	*	**	*	**	ns
Species (S) *F* test	**	***	*	**	***	**
W x S *F* test	**	*	*	*	ns	*
PPD *F* test	**	***	***	ns	***	ns
W x PPD *F* test	ns	ns	ns	ns	ns	ns
S x PPD *F* test	ns	ns	ns	*	ns	*
W x S x PPD *F* test	ns	ns	ns	ns	ns	ns
			%Ndfa			
Weed (W) *F* test	ns	ns	*	ns	ns	*
Species (S) *F* test	*	*	**	ns	***	*
W x S *F* test	ns	ns	*	ns	ns	*
PPD *F* test	ns	*	ns	ns	**	ns
W x PPD *F* test	ns	ns	ns	ns	ns	ns
S x PPD *F* test	ns	ns	ns	ns	***	ns
W x S x PPD *F* test	ns	ns	ns	ns	ns	ns

*, **, *** Significant at the 0.05, 0.01, 0.001 probability levels, respectively.

NS, nonsignificant at the 0.05 probability level.

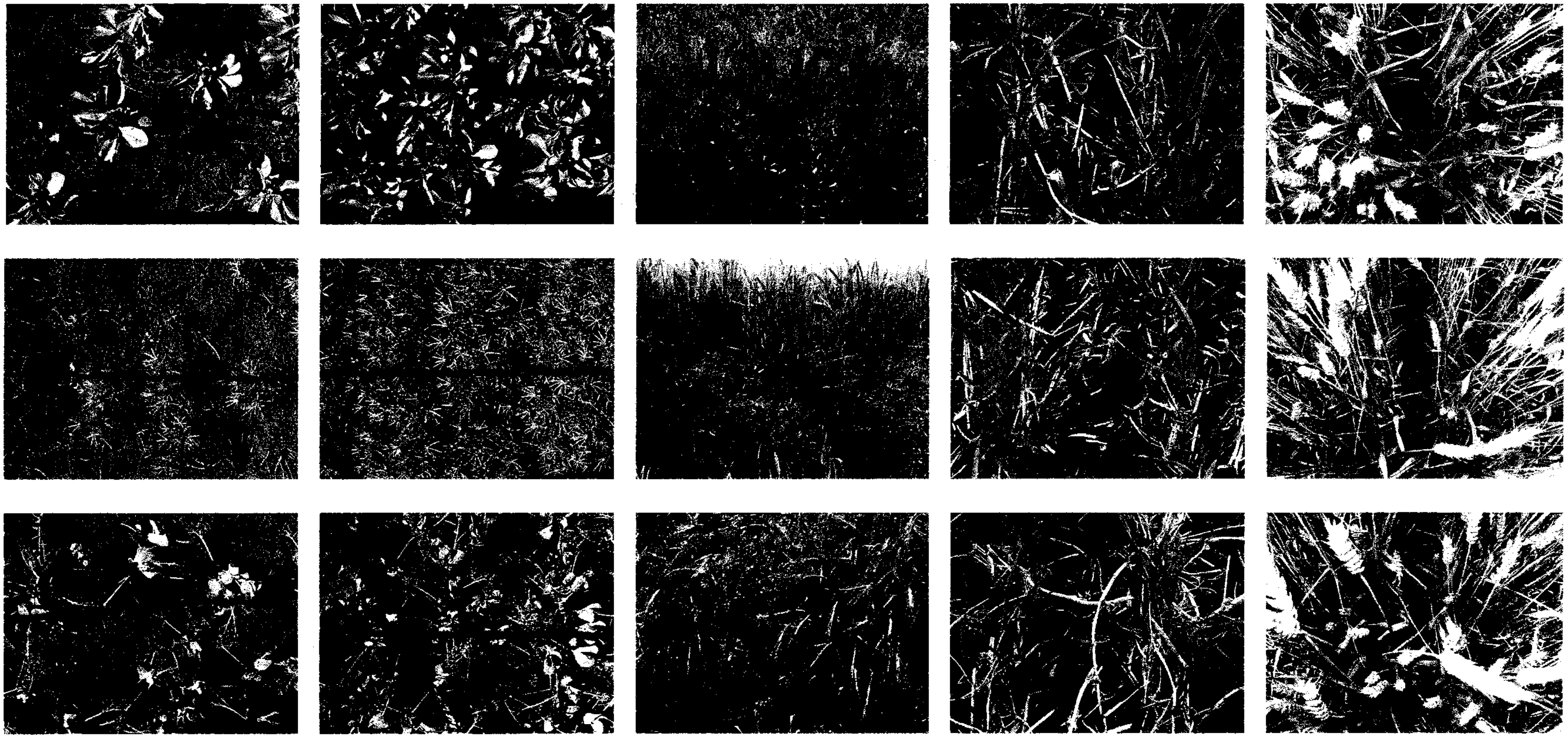


Plate 1. ‘Snowbird’ faba bean (upper row), Arabella’ lupin (center row), and ‘Cutlass’ field pea (lower row) growing at a low pulse planting density (far left column), a high pulse planting density (mid left column), in the presence of grassy weed pressure (center column), wheat seedlings growing on the respective pulse stubble types (mid right column), and maturing wheat growing on the respective stubble types (far right column) (Chapter 3).

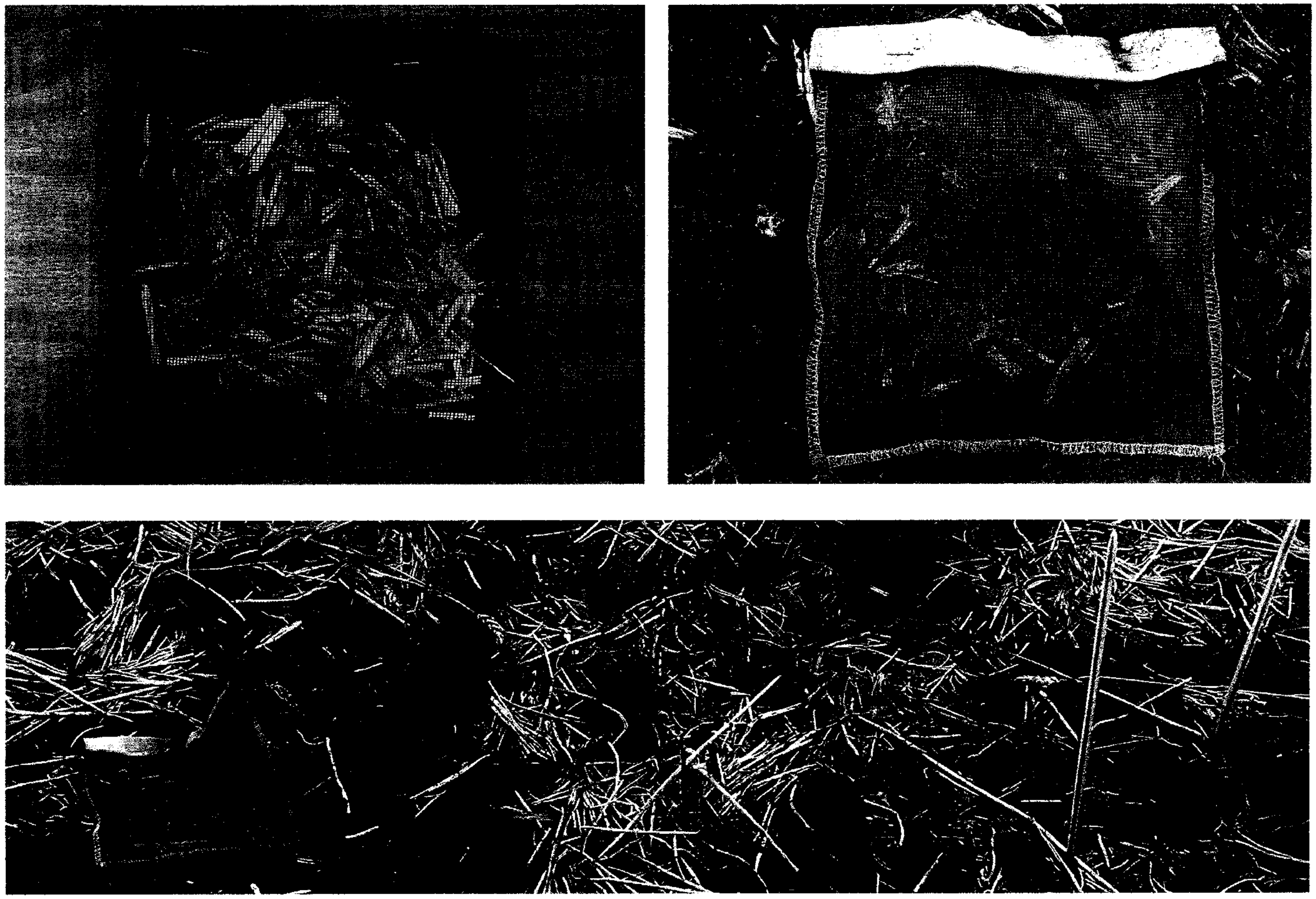


Plate 2. Undecomposed (upper left) and decomposed (upper right) 'Snowbird' tannin free faba bean crop residues in mesh litterbags, used to assess mass loss and nutrient release over a 22-month period. Field placement of above ground and below ground litterbags (lower center) (Chapter 4).

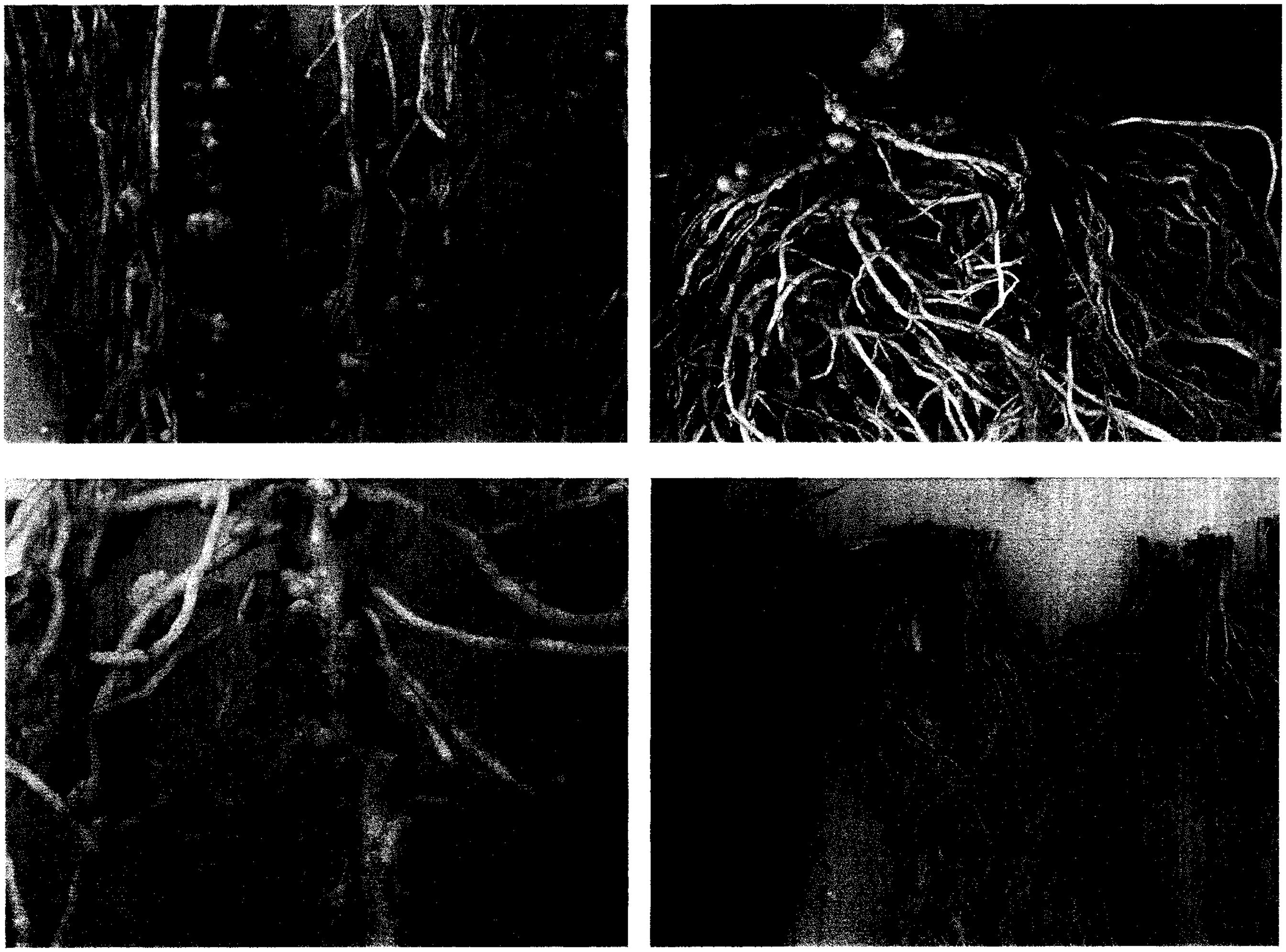


Plate 3. Nodulated pea roots (upper left), nodulated faba bean roots (upper right), nodulated lupin root (lower left) and barley roots from the pot study used to determine root biomass and N accumulation (Chapter 5).