Oilseed Crops for Semiarid Cropping Systems in the Northern Great Plains

Adrian M. Johnston,* Donald L. Tanaka, Perry R. Miller, Stewart A. Brandt, David C. Nielsen, Guy P. Lafond, and Neil R. Riveland

ABSTRACT

Oilseed crops are grown throughout the semiarid region of the northern Great Plains of North America for use as vegetable and industrial oils, spices, and birdfeed. In a region dominated by winter and spring wheat (*Triticum aestivum* L. emend. Thell.), the acceptance and production of another crop requires that it both has an agronomic benefit to the cropping system and improve the farmers' economic position. In this review, we compare the adaptation and rotational effects of oilseed crops in the northern Great Plains. Canola (*Brassica* sp.), mustard (*B. juncea* and *Sinapis alba* L.), and flax (*Linum usitatissimum* L.) are well adapted to cool, short-season conditions found on the Canadian prairies and northern Great Plains border states of the USA. Sunflower (*Helianthus annuus* L.) and safflower (*Carthamus tinctorius* L.) are better adapted to the longer growing season and warmer temperatures found in the northern and central Great Plains states. Examples are presented of how agronomic practices have been used to manipulate a crop's fit into a local environment, as demonstrated with the early spring and dormant seeding management of canola, and of the role of no-till seeding systems in allowing the establishment of small-seeded oilseed crops in semiarid regions. Continued evaluation of oilseed crops in rotation with cereals will further expand our understanding of how they can be used to strengthen the biological, economic, and environmental role of the region's cropping systems. Specific research needs for each oilseed crop have been recommended.

Oilseed crops are grown throughout the semiarid region of the northern Great Plains of North America for use as vegetable and industrial oils, spices, and birdfeed. In a region dominated by winter and spring wheat (*Triticum aestivum* L.), the acceptance and production of another crop requires that it both has an agronomic benefit to the cropping system and improves the farmers' economic position. Given that most oilseed crops have an indeterminate growth habit, adaptation is influenced by tolerance to high temperature and drought stress and by crop management to take advantage of optimum environmental conditions for flowering and seed fill. The increasing area of oilseed crop production is an indication of the success of plant breeders and agronomists in developing suitable cultivars and production methods in this semiarid region (Table 1).

While soybean [*Glycine max* (L.) Merr.] is the major oilseed crop produced in the USA, canola is the dominant oil crop in Canada. The cool climatic conditions characteristic of the Canadian prairies provide an ideal environment for *Brassica* spp. oilseeds and flax (Table 2) while the climate found in the USA is better suited to the warm season crops like soybean and sunflower. In the northern Great Plains, soybean is a relatively new crop finding a place in semiarid cropping systems with the development of early maturing, low heat–unit cultivars (Miller et al., 2002). As a result, the vast majority of soybean production in both the USA and Canada occurs in wetter regions east of the Great Plains. However, for the other oilseed crops listed in Table 1, the majority of production occurs within the northern Great Plains.

Diversification within cereal-based cropping systems can be critical to breaking pest infestations that are common with monoculture (Bailey et al., 1992, 2000; Elliot and Lynch, 1995; Holtzer et al., 1996; Krupinsky et al., 2002). Results of crop rotation studies in the Great Plains revealed that where oilseeds are adapted, their inclusion in rotation with cereals could increase net returns and reduce risk through improved production stability (Lafond et al., 1993; Dhuyvetter et al., 1996; Zentner et al., 2002). In addition, the yield of wheat was increased when following oilseeds in rotation, confirming that monoculture systems are the least effective means of optimizing wheat production (Lafond et al., 1992; Brandt and Zentner, 1995; Anderson et al., 1999).

The use of minimum and no-till seeding systems has been found to provide an effective means of controlling soil erosion in various regions of the Great Plains (Black and Power, 1965; Lindwall and Anderson, 1981). Improvements in seed yield with conservation tillage have been reported as a result of increased levels of plant-available water throughout the soil profile in the spring (Aase and Reitz, 1989; Brandt, 1992; Lafond et al., 1992) and increased water use efficiency due to favorable microclimate conditions created by standing stubble (Cutforth and McConkey, 1997). Some oilseed crops are small seeded, requiring good surface soil moisture for seed germination and crop establishment, as is effectively provided in direct-seeding systems in the northern Great Plains. As a result, adoption of conservation tillage management not only reduces soil loss by erosion, but also can facilitate extending the crop rotation and allowing for diversification of the crops grown. Economic success with a diversified crop rotation has been reported to be improved with the implementation of conservation tillage practices, such as minimum and zero-tillage (Lafond et al., 1993; Rossetti et al., 1999; Zentner et al., 2002).

The objective of this review is to summarize information on the adaptation and production potential of some

A.M. Johnston, Potash and Phosphate Inst. of Canada, 12-425 Pinehouse Dr., Saskatoon, SK, Canada S7K 5K2; D.L. Tanaka, USDA-ARS, Northern Great Plains Res. Lab., Box 459, Mandan, ND 58554; P.R. Miller, Montana State Univ., Dep. of Land Resour. and Environ. Sci., P.O. Box 173120, Bozeman, MT 59717-3120; S.A. Brandt, Agric. and Agri-Food Can., Box 10, Scott, SK, Canada S0K 4A0; D.C. Nielsen, USDA-ARS, Cent. Great Plains Res. Stn., 40335 Country Rd. GG, Akron, CO 80720; G.P. Lafond, Agric. and Agri-Food Can., Box 760, Indian Head, SK, Canada S0G 2K0; and N.R. Riveland, North Dakota State Univ., Williston Res. Ext. Cent., 14120 Hwy. 2, Williston, ND 58101-8629. Saskatoon Res. Cent. Publ. 1421. Received 1 Dec. 2000. *Corresponding author (ajohnston@ppi-ppic.org).

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Table 1. Harvested area of oilseed crops common to both the USA and Canada, 1988 and 1998 (FAO Stat., 1999).

	USA		Canada	
Crop	1988	1998	1988	1998
	Harvested area, 1000s of ha			
Soybean	23 218	28 657 (2160)†	533	980 (9)
Canola (rapeseed)	12	444	3672	5421
Sunflower	777	1 407	41	69
Safflower	104	115	0	3
Flax (linseed)	92	133	501	874
Mustard	8	39	171	279

† Values in parentheses are areas grown on the northern Great Plains.

oilseed crops in dryland rotation with cereals in the northern Great Plains. Data has also been included from Akron, CO. Although located in the central Great Plains, it has similar climatic conditions to the northern Great Plains because of its high elevation. The oilseed crops of interest include canola, flax, mustard, sunflower and safflower. Soybean, while an oilseed, has been addressed in an associated review of grain legumes by Miller et al. (2002). Information will be presented from a variety of locations, representing a wide range of environmental conditions (Table 2).

CANOLA

The oilseed genus *Brassica*, including canola and mustard, is part of the cruciferous family of crops. Cruciferous crops are widely adapted and cultivated around the world for human consumption, as a spice, and for livestock feed (Downey et al., 1974). Native to Asia and the Mediterranean region, rapeseed (*B. napus* and *B. rapa*) oil was originally used mainly as a lamp oil, with limited use in cooking. Rapeseed was first grown in North America to increase its production for marine oil during World War II. After the war, plant-breeding efforts in Canada resulted in improvements in the fatty acid composition of the oil (reduction of erucic acid) and a marked reduction in the level of glucosinolates in the meal. Together, these two improvements have made rapeseed the world's third most important vegetable oil, after soybean and palm (*Elaeis guineensis* Jacq.) oil (Downey and Rimmer, 1993). These modifications to the oil and meal of rapeseed led to the development of the name *canola* as a means of distinguishing the edible oil quality rapeseed from industrial quality oil (high erucic acid). Extraction of seed oil is high, with average oil content of 42% and a protein content of approximately 21% (DeClercq and Daun, 1999a).

Canola is cultivated widely on the northern Great Plains as a spring crop because sufficient winter hardiness has not yet been developed. The spring growth habit also fits well for canola as a summer crop in rotation before winter wheat in the coolest parts of the central Great Plains (Nielsen, 1997, 1998a).

Crop Water Use

Field assessment of *B. napus* indicates that it is capable of extracting water from depths of 114 to 165 cm (Table 3). The shallow measurement of 114 cm was an actual root observation and more accurately represents rooting depth than the deeper estimates, which were based on water extraction. Nielsen (1997) reported that while neutron scatter measurements found that canola extracted water to depths of 165 cm, 92 to 95% of the growing season water use of the crop came from the surface 119 cm of soil profile. *Brassica* spp. have a taproot system giving the crop access to deep water and nutrients (Downey et al., 1974). When grown in semiarid regions, the rooting characteristics of canola require adequate subsoil moisture to sustain the crop during flowering and seed filling. In those areas of the northern Great Plains where growing season water deficit is high, canola should be grown on summer fallow rather than continuous crop. Root growth rates for canola were greater than several other spring crops in a multiyear study at Swift Current, SK, more quickly depleting soil moisture reserves, and thus sooner becoming dependent on rainfall to sustain growth (Angadi et al., 1999b).

In the semiarid region of the Canadian prairies, seed yield response to water use from trials conducted at Swift Current and Scott, SK, indicated little difference between *B. napus* and *B. rapa* (Table 4). Once the minimum water use of approximately 127 mm was achieved, seed yield increased at a rate of 6.9 to 7.2 kg ha^{-1} mm^{-1}. While the base water use was higher at Akron, CO, so was the conversion efficiency at 7.7 kg ha^{-1} mm^{-1}, resulting in similar water use–yield predictions between these two studies separated by 10 degrees of latitude.

Table 2. Climatic attributes of selected locations throughout the northern Great Plains.†

Location	Lat (N)	Long (W)	Elev.	T‡	Precip.§	PE¶	DD_5#
	degrees		m	°C	mm	May–Aug.	
Melfort, SK	52.8	104.6	480	0.8	400	780††	1210
Scott, SK	52.4	108.8	660	1.5	360	910††	1180
Indian Head, SK	50.5	103.7	580	2.5	430	na	1310
Swift Current, SK	50.3	107.6	830	3.7	330	1000	1310
Williston, ND	48.1	103.8	640	5.8	350	na	1670
Mandan, ND	46.8	100.9	549	5.0	402	na	na
Akron, CO	40.2	103.2	1384	9.3	406	1134‡‡	1787

† Canadian data was obtained primarily from Environment Canada (1993) and U.S. data from the High Plains Regional Climate Center (2001). Data for potential evaporation were obtained by consulting weather records from each research center location.
‡ Mean annual temperature, 1961–1990.
§ Mean annual precipitation, 1961–1990.
¶ Mean seasonal Class A pan evaporation, 1961–1990.
# Mean seasonal cumulative degree days with a 5°C base, 1961–1990.
†† 1951–1980.
‡‡ 1967–1996.

Table 3. Estimated rooting depth for canola, flax, safflower, and sunflower grown at select locations across the northern Great Plains.

Crop	Estimated rooting depth	Comments method of determination	Source
	cm		
Canola			
B. napus (cv. Cyclone)	120	Neutron probe	Angadi and Entz, unpubl. data, 1998 (MB)
Rapeseed (cultivar unknown)	150	Unknown	Black et al., 1981 (ND)
B. napus (cv. Westar)	165	Neutron probe	Nielsen, 1997 (CO)
B. rapa (cv. Reward)	114	MRMV†	Merrill et al., 2000 (ND)
Flax (cv. Norlin)	61–76	Neutron probe	Lafond, unpubl. data, 1995 (SK)
Sunflower			
cv. Triumph 546	178	Neutron probe	Nielsen, 1998a (CO)
cultivar unknown	200	Unknown	Black et al., 1981 (ND)
cv. Pioneer 6339 and Cenex 803	145	MRMV	Merrill et al., 2000 (ND)
tall hybrid (cv. IS6111)	160	Neutron probe	Angadi and Entz, unpubl. data, 1998 (MB)
Safflower			
cultivar unknown	210–220	Unknown	Black et al., 1981 (ND)
cv. Montola 2000	164	MRMV	Merrill et al., 2000 (ND)

† Minirhizotron microvideo system (Merrill et al., 2000).

In the subhumid regions of the Canadian prairies, canola has been shown to have even higher water use efficiency, at 8.3 to 11.4 kg ha^{-1} mm^{-1}, reflecting the lower air temperatures and lower moisture deficits in this region (Johnston et al., 1996). Thus, water use efficiency is partially a function of crop adaptation.

Canola is a cool-season crop, with the duration of flowering having a strong influence on final seed yield (Nuttall et al., 1992; Brandt and McGregor, 1997; Angadi et al., 1999b). Heat stress during flowering of a canola crop can prematurely end flowering, resulting in limited seed set after the accumulation of large amounts of dry matter. Optimal daytime temperatures during flowering of 28°C for *B. rapa* and 20°C for *B. napus* indicate considerable difference in tolerance to air temperature between species (Angadi et al., 1999b). Nuttall et al. (1992) reported that a 3°C rise in maximum daily temperature (21–24°C) during flowering in July and August resulted in a 430 kg ha^{-1} decline in canola seed yield. Similar negative effects on seed yield have been observed with water stress during flowering and seed filling (Stoker and Carter, 1984; Nielsen, 1997). Water stress on the crop at flowering negatively influenced the formation of pods and seed size, resulting in lower final seed yield. Together, growing season precipitation and air temperature have been found to be good indicators of canola yield potential (Nuttall et al., 1992; Brandt and McGregor, 1997). Brandt and McGregor (1997) reported that the yield of canola on summer fallow at Scott, SK, was found to be closely related to temperature during flowering and early seed development while precipitation from early seed development through seed filling is essential to achieving full yield potential (see Eq. 1).

$$\begin{aligned}\text{Yield of } B.\ napus &= 4323 + 5.90 \times \text{Precip}\\ &\quad - 187.7 \times \text{Temp.}\\ &\quad R^2 = 0.76;\ \text{SE} = 221 \qquad [1]\\ \text{Yield of } B.\ rapa &= 4836 + 3.33 \times \text{Precip}\\ &\quad - 216.7 \times \text{Temp.}\\ &\quad R^2 = 0.72;\ \text{SE} = 200\end{aligned}$$

where Precip (mm) = 21 June–20 Aug. (*B. napus* R^2 = 0.83; *B. rapa* R^2 = 0.82) and Temp (°C) = 15 June–15 Aug. mean daily temperature (*B. napus* $R^2 = -0.58$; *B. rapa* $R^2 = -0.52$).

This relationship indicates that for each degree rise in mean daily temperature, the yield of *B. napus* declines by 188 kg ha^{-1} and *B. rapa* by 217 kg ha^{-1}. This indication of greater heat sensitivity for *B. rapa* contrasts with the observations in controlled environment conditions by Angadi et al. (1999a). Also, for each millimeter increase in precipitation, there is a corresponding 5.9 kg ha^{-1} yield increase with *B. napus* and 3.3 kg ha^{-1} yield increase with *B. rapa*, indicating a marked difference in water use sensitivity, contrasting with the equations presented in Table 4. Given that Brandt and McGregor (1997) used a common measurement period for their water use assessment and that *B. rapa* starts and finishes flowering 2 wk before *B. napus*, they may have introduced some bias into their evaluation of these crops.

Table 4. Estimated seed yield response to crop water use for canola, mustard, flax, safflower, and sunflower grown at select locations across the northern Great Plains.

Crop	Equation	Source
Canola		
B. rapa	kg/ha = 6.9 (WU† − 121 mm) R^2 = 0.74, SE = 1.29	Brandt et al., unpubl. data, 1998 (SK)
B. napus	kg/ha = 7.2 (WU − 132 mm) R^2 = 0.62, SE = 1.77	Brandt et al., unpubl. data, 1998 (SK)
B. napus	kg/ha = 7.7 (WU − 160 mm) R^2 = 0.72, SE = 0.88	Nielsen, 1998a (CO)
Mustard		
B. juncea	kg/ha = 7.6 (WU − 141 mm) R^2 = 0.63, SE = 1.84	Brandt et al., unpubl. data, 1998 (SK)
S. alba	kg/ha = 4.6 (WU − 67 mm) R^2 = 0.53, SE = 1.44	Brandt et al., unpubl. data, 1998 (SK)
Flax	kg/ha = 7.6 (WU − 127 mm) R^2 = 0.71, SE = 153	Brandt et al., unpubl. data, 1998 (SK)
Sunflower	kg/ha = 6.6 (WU − 175 mm) R^2 = 0.80, SE = 0.37	Nielsen, 1999 (CO)
Safflower	kg/ha = 8.2 (WU − 233 mm) R^2 = NA‡, SE = NA	Nielsen, 1995 (CO)

† WU, water use.
‡ Data not available.

Canola Management in Rotation

Including canola in rotation with wheat can have a positive effect on wheat yield. Brandt and Zentner (1995) reported that spring wheat yields were 24% higher on canola stubble than when grown on wheat stubble in a continuous wheat rotation at Scott, SK. At Melfort, SK, wheat yields were 30% higher when grown following canola than following wheat (Zentner et al., 1986). The influence of the canola crop in breaking plant disease [*Septoria* spp. and tan spot (*Pyrenophora tritici-repentis*)] buildup in the rotation was suggested as the main benefit derived from the preceding canola crop. In southern Alberta, winter wheat yields were increased by 25% when grown on canola vs. winter wheat stubble (Larney and Lindwall, 1994).

Tillage studies with canola have found that the crop is well suited to no-till seeding (Lindwall et al., 1994). Canola seed yield on no-till ranged from 1 to 14% higher than on conventional tillage. In drier regions, the maintenance of surface soil moisture with no-till has improved establishment of small-seeded crops like canola, attested by numerous observations by agronomists. In addition, the high water use requirements of canola can benefit from any additional water stored in the profile of no-till fields and may have increased water use efficiency from the microclimate of standing cereal stubble (B. McConkey, personal communication, 1999).

Ludlow and Muchow (1990) pointed out in a review that the ability to match key phenological growth period of a crop to a less stressful growth period in the growing season can be an effective means of avoiding the negative impact of heat and drought stress. Seeding date has been found to be a very important management tool in minimizing the negative impact of high temperature and moisture stress during the critical flowering and seed-filling periods in canola. Delaying canola planting past mid-April to early May has been shown to result in final seed yields that were 22 to 38% lower than late fall or early spring (Johnson et al., 1995; Kirkland and Johnson, 2000; Brandt et al., 1999). In North Dakota, the reduction in canola yield with delayed seeding was attributed to fewer pods per plant, leading to a lower harvest index (Johnson et al., 1995). Research on the Canadian prairies reported that when freezing temperatures were recorded with early planting dates, they did not negatively affect crop survival as the young seedlings appear tolerant to cold stress if acclimated (Kirkland and Johnson, 2000). A combination of factors, including cultivars, stage of development, pattern and duration of freezing temperatures, surface residue cover, and proximity of the seedlings to the soil surface, all play a role in the reaction of the seedlings to freezing temperatures.

In Saskatchewan, where winter soil temperatures generally never rise above freezing, Kirkland and Johnson (2000) have taken the early seeding of canola one step further and evaluated dormant seeding of canola in the fall just before soil freeze-up. This dormant-seeded canola is ready to begin growth as soon as temperature and moisture conditions permit in the following spring. The researchers report that relative to the traditional mid-May seeding date, late-April and fall dormant seeding increased canola yields by 44 and 34%, respectively. While crop establishment with dormant seeding is usually never as good as that achieved with spring seeding, the adaptable nature of the canola crop allows it to compensate for a thin stand through increased branching. Additional advantages of dormant seeding included earlier crop flowering (25 d), windrowing (18 d), and harvesting (19 d) (Kirkland and Johnson, 2000).

MUSTARD

There are two species of mustard produced commercially in North America, *Sinapis alba* (white or yellow mustard) and *B. juncea* (brown and oriental mustard) (Forhan, 1994). As one of the first crops domesticated by man, the value of mustard as a spice rapidly spread it along the trade routes of the world. Before World War II, when mustard supplies to North America were disrupted, mustard was grown primarily in Western Europe. Similar to canola, mustard is a cool-season crop well suited to short growing season environments (90–110 d). While originally grown in the western USA, the crop is now primarily produced in the semiarid regions of western Canada (Table 1). Mustard production is used principally for human consumption as dry (40%) and prepared (60%) products (Forhan, 1994). While *B. juncea* is still grown as an edible oilseed in some parts of the world where strong-flavored oil is in demand, this is minor compared with the spice and condiment use for the crop.

Crop Water Use

Information on the water use characteristics of mustard was reported in recent research by Brandt et al. (1999), which included both *B. juncea* and *S. alba*. They report that *B. juncea* is very similar to canola in its conversion of water into seed yield (Table 4). However, while *S. alba* requires less water to establish its minimum seed yield, it also has much lower seed production per unit of water use relative to *B. juncea*. Angadi et al. (1999b) reported that *B. napus* and *B. juncea* were similar in their water use characteristics, and as a result, they concluded that despite its reputation as a drought-tolerant crop, mustard was no better adapted to semiarid regions than canola. In fact, the high water use characteristic and deep rooting pattern of the *Brassica* species of canola and mustard make them better suited than spring wheat or field pea (*Pisum sativum* L.) for production on summer fallow in semiarid regions (Brandt and McGregor, 1997). Given that summer fallow is no longer part of many cropping systems in semiarid regions, positioning canola in rotation following low water-use, shallow-rooted crops and optimizing water conservation with no-till seeding may be required to achieve successful production.

Optimum daytime air temperature for maximizing yield of *B. juncea* was similar to that of *B. rapa*, close to 28°C, and higher than the 20°C optimum for *B. napus* (Angadi et al., 1999a). Subjecting *Brassica* species to a high-temperature stress during the flowering stage of development using a temperature of 35 to 15°C (day and night, respectively) reduced the seed yield of *B. juncea* by 34% and *B. rapa* by as much as 93%. *Brassica napus* and *S. alba* both flowered with fewer accumulated heat units when seeded early rather than late (Miller et al., 1998a). Delayed seeding of *S. alba* resulted in the largest proportional (30%) reduction in seed yield among 12 cereal, oilseed, and pulse crops grown in a seeding date study at Scott and Swift Current, SK. For both *B. juncea* and *S. alba*, the reduction in seed size was equal in proportion to the reduction in pod density.

Mustard Management in Rotation

Little research has been conducted into the management of mustard in rotation with cereals in the northern Great Plains. In one cropping sequence study at Swift Current, SK, *B. juncea* did not increase seed yield of spring wheat significantly over that of continuous spring wheat though a small increase (0.5 protein units) in wheat grain protein was observed (Miller et al., 1998a). During one of eight site-years of that study, volunteer mustard seedlings competed strongly with spring wheat at the seedling stage, reducing wheat yield by 49% compared with continuous spring wheat, despite complete control with herbicide application within the recommended window. Given that mustard has a water use, rooting depth, and growth and development pattern similar to canola, it is likely to provide cropping system effects similar to canola (Angadi et al., 1999b). As discussed for canola above, optimizing the yield of *Brassica* sp. oilseeds in semiarid environments will depend on the timing of water and high-temperature stress relative to crop flowering and seed formation.

FLAX

Flax is an ancient crop belonging to the family Linaceae. Reports of its production go back to 3000 BC in Babylon (Flax Council of Canada, 1998). Cultivated flax consists of two main types, harvested for seed and harvested for fiber. In North America, primarily the oilseed type is grown, and flax production dates back 400 yr when Louis Hebert, the first farmer in Canada, brought it to New France. With time, flax production expanded westward and southward into the Great Plains. Flax oil is high in linolenic fatty acid (45–60%), making it a very effective drying agent. Although it is an edible oil, it is used primarily for industrial purposes, such as in the production of paints and oil-based coverings and in the manufacture of linoleum flooring (Flax Council of Canada, 1998). Linseed oil also offers important nutritional benefits because of the high levels of omega-3 fatty acids. Oil extraction in flax averages 44%, and the meal has an average protein content of 23% (DeClercq and Daun, 1999b). Recent plant-breeding achievements have led to the development of a new flax type called 'Solin', which is a name used for flax with low (<5%) linolenic acid in the oil (Dribnenki and Green, 1995). Solin, which responds agronomically as regular flax, is being developed exclusively for the edible oil market. In North America, all flaxseed is grown in the Great Plains region, with 35% of world production in Canada and 4% in the USA (Table 1).

Crop Water Use

Relative to the other oilseed crops, flax is a shallow-rooted crop (Table 3). Research on flax water use and extraction from the soil has shown that flax will extract 90% or more of plant-available water from the 0- to 60-cm soil layer (Lafond, unpublished data, 1998). In agreement, Campbell and Zentner (1996) showed that flax grown on fallow often conserved more water in the 60- to 120-cm soil layer than did spring wheat. Seed yield response to water use from trials conducted at Swift Current and Scott, SK, indicates little difference between flax and *B. napus* at the same location (Table 4). Once the minimum water use of approximately 127 mm was achieved, seed yield increased at a rate of 7.6 kg ha^{-1} mm^{-1}. However, at Indian Head, SK, 12 yr of water use (WU) data with flax gave a very poor relationship with seed yield [Yield (kg ha^{-1}) = 1.9 (WU + 532 mm); $r^2 = 0.06$]. This poor relationship at this higher-yielding location indicates that something other than water is influencing the seed yield response of flax (Lafond, unpublished data, 1998).

The shallow rooting behavior of the flax crop makes it well adapted to the improved moisture conditions of the surface soil found in no-till production systems (Lafond et al., 1992). The benefits of no-till production were demonstrated over a wide range of growing conditions, i.e., from hot and dry to cool and moist conditions (Lafond and Derksen, 1996). In fact, flax was shown to have greater water use efficiency under no-tillage (5.4 kg ha^{-1} mm^{-1}) relative to conventional tillage (4.9 kg ha^{-1} mm^{-1}).

Flax Management in Rotation

Although flax has been grown for a long time on the Canadian prairies and in the northern Great Plains of the USA, few rotational studies have included it (Lafond et al., 1992). Campbell and Zentner (1996) reported that flax conserved soil NO_3 and water below the 60-cm soil depth compared with spring wheat though it inexplicably failed to provide a rotational benefit to a subsequent wheat crop compared with continuous spring wheat. Soil under flax stubble dries and warms sooner than that under wheat stubble, and it is possible that timeliness of water use was compromised due to a common date for spring tillage operations, which had to be delayed until the wheat stubble was sufficiently dry. It has also been recommended that flax should not be grown after legumes or potato (*Solanum tuberosum* L.) because of the potential for infection from *Rhizoctonia* spp. bacteria (Flax Council of Canada, 1998). While the recommendations have never been substantiated, it is believed that flax grown after alfalfa does exceptionally well in subhumid regions of the Canadian prairies. Other studies that have examined flax from a crop rotation basis have revolved around seeding flax into canola stubble. These studies have shown that when young volunteer canola seedlings are tilled just before the seeding of flax, yield reduction is experienced, supposedly as a result of indole glucosinolates in the vegetative material inhibiting germination (Vera et al., 1987). However, this effect was muted and even eliminated when flax was seeded directly into canola stubble as in a no-till production system (Gubbels and Kenaschuk, 1989). A survey of the Manitoba Crop Insurance Database has revealed that the yields of spring wheat were generally higher following flax than following canola or field pea (Bourgeois and Entz, 1996). Compared with canola, this can be explained in part by the fact that the shallow-rooting behavior of flax would favor the deeper-rooting crops like wheat because of extra moisture and nutrients conserved below the 60-cm soil layer.

SUNFLOWER

Sunflower (*Helianthus annuus* L.) is well suited to warmer regions of the northern Great Plains. The cultivated sunflower is native to North America and consists of two types: (i) confectionary types, used for human consumption and bird food, and (ii) oilseed. Sunflower is a tall (100–180 cm) plant and produces seed with an oil content of 40% or more. The long-season growth habit of sunflower (95–130 d) makes it best suited to areas with a long frost-free period and high growing-season heat units. A wide range of sunflower cultivars are available, each with specific heat unit requirements. Sunflower cultivars range from 1140 to 1400 growing degree days using a 7°C base temperature (Robinson, 1971). Data from northeast Colorado with the same base temperature showed a growing degree-day requirement ranging from 1485 to 1595 (Nielsen, unpublished data, 1999). Most of the growing degree-day differences among cultivars occur during the period from emergence to floral initiation.

Crop Water Use

Sunflower is a deep-rooted crop that requires 10 to 30 d more to mature than cereals, making it a high water-use crop. Plant rooting depths of 120 to 269 cm have been reported (Table 3). Jaafar et al. (1993) found that sunflower in Kansas was rooting to a depth of 269 cm, with 87 to 96% of the roots observed in the surface 165 cm of the soil profile. Nielsen (1998a) also found that sunflower in northeastern Colorado extracted water to a depth of 165 cm and that it showed very uniform water extraction to this depth. Unlike canola, which developed a deeper and more prolific root system in a dry vs. wet growing season, sunflower was very consistent in its rooting depth and water extraction regardless of the growing season conditions (Nielsen, 1998a). On loam and silt-loam soil types, sunflower has been shown to be capable of extracting soil water to a lower matric potential than corn (*Zea mays* L.), proso millet (*Panicum miliaceum* L.), and winter wheat (Unger, 1990; Nielsen, unpublished data, 1995).

Work in Colorado indicated that sunflower seed yield was less responsive to water than canola (Table 4) (Nielsen, 1998a). Similar results were reported in work on early maturing open-pollinated, short-stature sunflower in a comparative trial with *B. juncea* at Swift Current, SK (Miller et al., 1998a). Miller et al. (1998b) concluded that short-stature sunflower used water inefficiently relative to mustard and, as such, may not be as well suited as other oilseed crops in semiarid regions. However, subsequent research with a dwarf hybrid sunflower, slightly later in maturity than the short-stature sunflower, showed water use efficiency equal to *B. juncea* (Miller et al., 1998a). Direct comparisons of water use efficiency between sunflower, a warm-season plant, and cool-season oilseeds are difficult to make accurately in the highly variable climatic conditions of the northern Great Plains. The much longer growth cycle of sunflower causes a higher likelihood of anthesis and seed fill occurring during summer drought. However, midsummer rainfall received after cool-season oilseeds have ceased growth can be converted efficiently to seed yield by sunflower. Also, the seeding date of sunflower is often delayed weeks to months after *Brassica* spp., indicating that these crops utilize the environment in completely different patterns. This may be because sunflower is a warm-season broadleaf and most of the preanthesis growth occurs during periods of high evapotranspiration demand, whereas *B. juncea* is a cool-season broadleaf and most of its vegetative growth occurs during the low evapotranspiration part of the growing season.

Sunflower Management in Rotation

Crop management trials in Colorado have found that sunflower fits well into cereal-based crop rotations but should not be grown more than once every 3 or 4 yr due to persistence of the damaging plant disease phoma (*Phoma macdonaldii* Boerma) (Anderson et al., 1999). The high water use of sunflower reduced the yield of subsequent crops in rotation, especially during dry years. Results from a crop rotation study at Akron, CO, showed reduced average yields of winter wheat when the crop was grown following sunflower in rotation compared with rotations without sunflower (Nielsen et al., 1999). Yield reductions were much larger in a 3-yr rotation (wheat–sunflower–fallow) than in 4-yr rotations (wheat–corn–sunflower–fallow or wheat–millet–sunflower–fallow). In wet years, the yield-reducing effect of the previous sunflower crop was not evident in the 4-yr rotations but still manifested itself in the 3-yr rotation.

To reduce the potential for crop failure after sunflower, good soil and water conservation practices need to be used, and a drought-tolerant crop should be planted that uses water efficiently. Nielson (1998b) showed that much of the detrimental effect of the high soil water extraction by sunflower could be offset when sunflower stalks are left standing after harvest. In years with normal to above-normal snowfall in the central Great Plains, 6 to 15 cm of soil water recharge can occur while concurrently providing adequate protection against wind erosion (Nielsen and Aiken, 1998).

Wind erosion potential and soil water evaporation are minimized when no-till or reduced-till weed control and sunflower-planting practices are employed to maintain previous crop residues on the soil surface during the sunflower growing season. In recent years, there has been increased interest in minimum- and no-till sunflower production practices (Blamey et al., 1997). Maintaining surface residue from the previous crop results in reduced soil erosion and evaporation and increased rainfall infiltration and soil water storage. Maintaining surface residue using no-till helped suppress evaporation and increased sunflower seed yield 16% compared with conventional tillage (Norwood, 1999).

The maintenance of surface crop residues in sunflower rotations helped to reduce or prevent the buildup of certain weed species. Weed populations often proliferate within the open canopy of sunflower, but combining cultural practices, such as delayed seeding, narrow rows, banded fertilizer, and increased plant population, has improved weed control (Tanaka and Anderson, 1999).

SAFFLOWER

Safflower is a member of the Compositae or Asteraceae family and provides three products: an edible oil, meal, and birdseed. Historically, safflower was grown for its flowers, with the florets being used for coloring and flavoring foods, for making dyes, and as medicines (Mundel et al., 1992). It is one of humanity's oldest crops and was usually grown in small plots for a grower's personal use. Safflower is a thistle-like annual herbaceous plant with long, sharp thorns that is grown mainly in arid and semiarid areas of the world. Currently, it remains a minor crop, with world seed production around 800 000 t annually (Gyulai, 1996).

The crop was introduced into North America as early as 1899 from its origin in the Middle East and South Asia. Safflower was initially tested in the USA in 1925 as a new oilseed crop and was commercially grown in the Great Plains beginning in the late 1950s (Knowles, 1958). Oil content of safflower seed ranges from 35 to 40%. There are two types of safflower cultivars: those producing oil high in oleic or monounsaturated fatty acid and those high in linoleic polyunsaturated fatty acid (Berglund et al., 1998). After oil extraction, the seed meal has a protein content of about 24% (Hoag et al., 1969). Safflower seed that is uniformly bright white in color or lightly striped can be marketed as birdseed.

Crop Water Use

Safflower generally is considered a daylength-neutral, long-day plant that needs at least 1400 degree days (5°C basis) to reach maturity. Miller et al. (2001) used a very early maturing cultivar of safflower (Saffire) to calculate degree-day requirements of 1430 to 1480 at Swift Current, SK, concluding that maturity requirements for safflower generally were too great for that location. Plants have a deep taproot that can extend to a depth of 220 cm (Table 3) and xerophytic spine attributes that contribute to good drought and heat tolerance (Dajue and Mundel, 1996). Safflower will not survive in standing water for even a few hours during warm weather (Mundel et al., 1997). Therefore, good estimates of yield per unit of water are difficult to determine. Research at Mandan, ND, found that the water use efficiency of safflower ranged from 1.2 to 5.1 kg ha^{-1} mm^{-1} for crops seeded mid-May or early June (Alessi et al., 1981). Studies conducted by Hang and Evans (1985) using a line-source irrigation method determined that safflower's water use efficiency was 8.45 kg ha^{-1} mm^{-1} at 50 cm of irrigation. In north-central Montana, Brown and Carlson (1990) collected water use data in safflower cultivar trials over 10 yr, generating a rainfed yield–water use equation of:

$$\text{Seed yield (kg ha}^{-1}) = 7.2(\text{evapotranspiration} - 185 \text{ mm}) \qquad [2]$$

Water use was estimated based on soil water extraction to an assumed 213-cm soil depth, with an estimated 254 mm of plant-available water. The Brown and Carlson (1990) equation appears similar to the high end of the range reported by Alessi et al. (1981). In general, safflower grown in the northern Great Plains of the USA yields best in areas where along with good soil moisture at seeding, growing season precipitation (May through August) is in the 15- to 25-cm range, with at least 75% of the precipitation occurring before the end of July. The flowering and pollination of safflower can be severely reduced by rainy days or days with excessive dew and high humidity. Plant diseases such as alternaria (*Alternaria carthami*) and bacterial blight also flourish under these conditions and can cause major yield reductions.

Safflower in Rotations

Including safflower in wheat-based rotations can improve use of deep soil water and N (Black, 1993). The long growing season required by the crop permits deep root growth, enabling safflower to use water and nutrients from a greater soil depth than crops with a shorter growing season. Because safflower uses more soil water and requires a longer growing season than small grain crops, it and other crops of similar rooting depth should be grown in 3-yr or longer rotations to reduce potential failure of other crops in a rotation. In areas that have dryland saline-seep problems, safflower can be used in rotation to use surplus water from recharge areas to prevent the expansion of saline seeps (Mundel et al., 1992). Control of grassy weeds in safflower can benefit subsequent small grain crops in a rotation. Conversely, broadleaf weed control in small grains can also benefit safflower production because few herbicides are registered for use in this minor crop.

OILSEED CROP RESEARCH NEEDS IN THE NORTHERN GREAT PLAINS

The successful use of oilseed crops to diversify cropping systems in the northern Great Plains has been demonstrated in this review. The oilseeds canola, mustard, and flax are well adapted to cool, short-season conditions found on the Canadian prairies and northern border states of the USA. Sunflower and safflower are better adapted to the longer growing season and warmer temperatures found in the northern and central Great Plains states. However, agronomic practices can manipulate a crop's fit into a local environment, as demonstrated with the early spring and dormant seeding management of canola and the role of no-till seeding systems in allowing the establishment of small-seeded oilseed crops in semiarid regions. Continued evaluation of oilseeds in rotation with cereals will further expand our understanding of how these crops can be used to strengthen the biological, economic, and environmental role of the region's cropping systems. Specific research needs for each oilseed crop are suggested.

Canola and mustard crops are capable of producing large amounts of crop biomass under conditions of good early season moisture and warm temperature. However, low-water and high-temperature stress conditions during flowering and seed filling can result in poor seed formation and a very low harvest index. There is a need to continue to evaluate canola and mustard cultivars under high-stress environments to determine if there are plant types better suited to these environments, with conservative growth habits that are better matched to soil water constraints. Further research is required across the semiarid regions of the northern and central Great Plains to evaluate the full impact of alternative seeding dates on the suitability of *Brassica* sp. oilseeds in cropping systems. This type of seeding-date manipulation may greatly expand the production area of these cool-season oilseed crops.

The authors' understanding of the water use characteristics and yield potential of flax is very poor. In the more humid areas of the northern Great Plains, there is a need to understand why the positive relationship between seed and water use becomes very weak as available water and water use increases. However, likely the greatest need for research in flax is to develop a better understanding of yield formation, with an emphasis on which management practices have the greatest influence on yield and how this knowledge can be used in the development of new flax cultivars.

Future research needs to continue to define where sunflower has the best fit in the overall crop production system. The role of a deep-rooted crop like sunflower in utilizing subsoil moisture and nutrients has not been fully exploited in cropping systems where both deep- and shallow-rooted crops are grown.

Safflower seedlings lack the vigor displayed by many other crops (Berglund et al., 1998). Spring stand establishment is a major problem in the northern Great Plains because of inadequate seed–soil contact, soil crusting, lack of adequate soil moisture in the seedbed, or seedling diseases. Early spring planting can also be a problem because of cool soil temperatures. Future research areas for safflower include improving seedling vigor, improving seed dormancy to minimize sprouting at harvest, increasing seedling cold tolerance, developing seeding techniques, and other management practices to improve spring stand establishment, including those improving resistance to seedling disease. Areas such as weed control, rotations, and value-added products are major research topics currently being pursued. But one research area that the safflower industry sorely needs is marketing research and creation of a national organization to promote safflower as a very healthy, edible oil; viable industrial oil, and food for birds.

The successful inclusion of oilseed crops in cereal-based cropping systems has been shown in this review to have positive agronomic and economic impacts. Genetic improvement in oilseed crop yields will continue to make them economically competitive with cereals. Evaluation of oilseed crops through agronomic management will ensure their role as a diversification option in Great Plains cropping systems.

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Potential of Forages to Diversify Cropping Systems in the Northern Great Plains

Martin H. Entz,* Vern S. Baron, Patrick M. Carr, Dwain W. Meyer, S. Ray Smith, Jr., and W. Paul McCaughey

ABSTRACT

Cultivated forage crops are grown on almost 12 million ha on the northern Great Plains. This paper reviews the benefits of diversifying annual crop rotations with forage crops and highlights innovations in forage systems. Agronomic benefits of rotating forage crops with annual grain crops include higher grain crop yields following forages (up to 13 yr in one study), shifts in the weed population away from arable crop weeds, and improved soil quality. Perennial legumes in rotation also reduce energy requirements by adding significant amounts of N to the soil. Soil water availability may limit the extent to which forages benefit following crops. Under semiarid conditions, forages can actually reduce yields of the following crops, and as such, tillage practices that conserve soil water have been developed to partially address this problem. Forages in rotation provide environmental benefits, such as C sequestration, critical habitat for wildlife, and reduced NO_3 leaching. A wider range of annual plant species are now used in forage systems in an effort to extend the grazing season and to maximize use of water resources. Intensive pasture management using cultivated forages is on the increase as is the use of alfalfa (*Medicago sativa* L.) in grazing systems; in some cases, bloat-reduced alfalfa cultivars are used. Pasture-based systems appear to provide benefits for both animal and human health and arguably the health of the environment. Pasture systems are less nutrient exhausting than hay systems. As a result, nutrient management strategies will differ in the following crop. Additional research is required to optimize the role of cultivated pastures in grain-based cropping systems.

FORAGE PRODUCTION in the northern Great Plains (NGP) of the USA and Canada involves cultivated and native pasture and hay production. The area dedicated to cultivated forage crop production in the three Canadian prairie provinces (Manitoba, Saskatchewan, and Alberta) and three U.S. states (North Dakota, South Dakota, and Montana) totals 7.8 million ha of cultivated hay and 3.8 million ha of cultivated pasture (Alberta Agric., Food, and Rural Dev., 1999; Manitoba Agric. and Food, 1999; Saskatchewan Agric. and Food, 1999; NASS, 1999). Many farmers and ranchers use cultivated forages to complement the approximate 44 million ha (Alberta Agric., Food, and Rural Dev., 1999; Manitoba Agric. and Food, 1999; Saskatchewan Agric. and Food, 1999; NASS, 1999) of native rangeland in this region.

Forage is produced and conserved during the short growing season and fed during the remainder of the year. Hay is the predominant winter feed, followed by straw, silage, stockpiled perennial pasture, and swathed annual pastures (Small and McCaughey, 1999). The winter feeding period for beef cattle (*Bos taurus*) in western Canada is widely reported to exceed 200 d per year (Mathison, 1993). However, this varies by region and year, mainly depending on period of snow cover. In Alberta during 1999, the mixed grassland region, most representative of the NGP area, had an average 155 winter feeding days compared with 201 in the boreal transition zone, which lies to the north of the prairie (Anonymous, 2000). Approximately 10% of forage production is used for dairy cows located in the NGP region. Some forage is also exported outside North America [e.g., dehydrated alfalfa cubes and pellets and compacted timothy (*Phleum pratense* L.) hay]. Very little forage is typcially imported into this region although redistribution of forage does occur when localized droughts reduce forage supply.

Alfalfa is the main forage legume and is grown on 61% of cultivated forage hayland in the U.S. NGP. Alfalfa's role in grazing systems is increasing (Smith and

M.H. Entz, Dep. of Plant Sci., Univ. of Manitoba, Winnipeg, MB, Canada R3T 2N2; V.S. Baron, Agric. and Agri-Food Can., Lacombe Res. Cent., Lacombe, AB, Canada T4L 1W1; P.M. Carr, North Dakota State Univ., Dickinson Res. and Ext. Cent., 1089 State Ave., Dickinson, ND 58601; D.W. Meyer, Dep. of Plant Sci., North Dakota State Univ., Fargo, ND 58105; S.R. Smith, Jr., Dep. of Crop, Soil, and Environ. Sci., 424 Smyth Hall, Virginia Tech, Blacksburg, VA 24061-0404; and W.P. McCaughey, Agric. and Agri-Food Can., Brandon Res. Cent., Brandon, MB, Canada R7A 5Y3. Received 22 Jan. 2001. *Corresponding author (m_entz@umanitoba.ca).

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Abbreviations: CLA, conjugated linoleic acid; DM, dry matter; NGP, northern Great Plains.