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

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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

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

Singh, 2000). Other forage legumes are also grown where alfalfa is not adapted [e.g., red clover (*Trifolium pratense* L.) and alsike clover (*T. hybridium* L.) in wetter and acid soil zones, sainfoin (*Onobrychis viciafolia* L.) in dryland pastures, or where a nonbloating legume is desired]. There is significant potential to utilize these better adapted, alternative perennial forage legumes in the region though grower education is required. Many different grass species are used in cultivated forage systems, ranging from the drought- and salt-tolerant wheatgrasses (*Agropyron* spp.) to flooding-tolerant reed canarygrasses (*Phalaris* spp.). Many annual C_3 and C_4 plant species are used to fill gaps in the feed supply (Kilcher and Heinrichs, 1961; Baron et al., 1992; Carr et al., 1998). Forage is defined as, "any plant whose vegetation is eaten by livestock" (Heath et al., 1973), and as such, many different plants are used, including crop residues (e.g., corn stalks and chaff) and hay harvested for remnant areas and roadside ditches. These forage sources are especially important in drought years such as 2000 in Montana. Forage seed production is also an important industry in the region though it occupies a relatively small area compared with forage production.

The percent of arable cropland that is rotated with forage ranges from 5 to 15% in the region. Two recent surveys have characterized forage and beef production in western Canada (Entz et al., 1995; Small and McCaughey, 1999).

Objectives of this paper are to (i) review agronomic, economic, and environmental benefits and risks of diversifying cropping systems with forage crops; (ii) identify means to enhance the positive attributes of forages in NGP cropping systems and to make forages a more important component of the cropping system; and (iii) highlight research challenges for the future.

ROTATIONAL BENEFITS OF FORAGES IN THE NORTHERN GREAT PLAINS CROPPING SYSTEMS

Forage benefits have received less attention in the NGP than elsewhere, such as the humid U.S. Midwest where alfalfa has traditionally been rotated with grain crops or areas of Australia where unique, self-regenerating forage species are grown in grain-based cropping systems (Grace et al., 1995). The short growing season and relatively dry conditions (i.e., low precipitation and high evaporative demand for water) in the NGP will modify rotational benefits of forages relative to wetter areas.

Some of the best information on forage rotational benefits in the NGP has come from long-term crop rotation studies, many of which were established soon after European settlement in the USA (Stoa and Zubriski, 1969) and Canada (Campbell et al., 1990).

Rotational Yield Benefits

Many NGP researchers have reported rotational yield benefits from perennial forages. In a long-term (1912–1956) study at Fargo, ND, Stoa and Zubriski (1969) reported that wheat (*Triticum aestivum* L.) yields were 50% higher from land previously cropped to alfalfa for 3 yr than from land previously cropped to nonlegumes such as corn (*Zea mays* L.), wheat, or flax (*Linum usitatissimum* L.). Similar results continue to be reported from studies at Melfort, SK (Campbell et al., 1990); Winnipeg, MB (Poyser et al., 1957); and Lethbridge, AB (Ellert, 1995) as well as from two ongoing classical long-term studies of crop rotation in western Canada: The University of Alberta's Breton Plots (initiated in 1930) (Ellert, 1995) and Agriculture and Agri-Food Canada's long-term study at Indian Head, SK (initiated in 1958) (Campbell et al., 1990).

In a survey of Manitoba and Saskatchewan forage producers, 71% of respondents indicated higher grain yields after forages than in annual crop rotations (Entz et al., 1995). Rotational yield benefits were greatest in eastern and northern zones and lowest in drier, western and southern zones. In one of the best studies ever published on the long-term residual yield benefits of including forage in a cropping system (McLennan, AB), Hoyt (1990) reported that for the first 8 yr after forage termination, wheat yields were 66 to 114% greater after forage relative to continuous wheat. Yield differences started to decline after 8 yr although wheat yields in the alfalfa systems were still higher ($P < 0.05$) than the control in the 10th and 13th year after sward breaking.

In areas of the NGP where water seriously limits crop productivity, inclusion of perennial forages can reduce crop yield in following crops due to forage-induced drought. Working in west-central Saskatchewan, Brandt and Keys (1982) determined that available soil water in spring was lower after a 2-yr alfalfa crop than in a continuous grain rotation. A full year of fallow was insufficient to fully replenish the soil profile with water in the alfalfa system relative to the grain system. In central Saskatchewan, Austenson et al. (1970) reported that alfalfa in rotation depressed wheat yield in the first crop after breaking even after a full year of summer fallow. Interestingly, they observed that alfalfa with bromegrass (*Bromus inermis* Leyss.) or bromegrass alone did not affect wheat yields significantly. Others (e.g., C.A. Campbell, personal communication, 2000) have suggested that low cereal yields after alfalfa could be due to allelopathic effects from alfalfa, and such effects are greatest under dry soil conditions. However, no studies have been conducted to substantiate this suggestion.

In wetter areas of the NGP, these water-depleting characteristics of alfalfa and other perennial forages are often viewed as desirable. For example, dewatering characteristics of perennial forages play an important role in soil salinity management. Soil salinization is a threat to the long-term sustainability of crop production on approximately 25% of NGP cropland (Morrison and Kraft, 1994). Examples of successful salinity control with alfalfa (Eilers, 1989, p. 78, as cited in Morrison and Kraft, 1994) and perennial grasses (D. Wentz, personal communication, 1996) have been documented. Hoyt and Leitch (1983) reported that the subsoil (60–135 cm) dewatering effect with perennial legumes lasted for at least 2 yr after stand termination and that alfalfa provided greater dewatering benefits than red clover. Dewatering benefits with alfalfa on a clay soil in Manitoba resulted in higher wheat yields in alfalfa-based vs. annual grain-based rotations (Forster, 1998).

Grazing management and plant species impact soil water availability and potential evapotranspiration. Perennials begin to dewater soil as soon as growth begins in the spring (April), whereas annuals only begin to reduce soil-available water when ground cover has been achieved (mid-June) (Twerdorff et al., 1999a). In research in central Alberta, greater evapotranspiration by perennials reduced surface (0 to 7.5 cm) soil water more than annuals did until mid-July, after which annuals and perennials had similar surface soil water contents. Generally, surface soil water was higher under heavy compared with light grazing intensities for perennial grasses (Twerdoff et al., 1999b). Seasonal evapotranspiration was generally greater for perennials than for annuals. Water use efficiency for perennials [16.6 kg dry matter (DM) ha^{-1} mm^{-1}] was 1.4 times greater than for annuals (11.6 kg DM ha^{-1} mm^{-1}). However, heavy grazing intensities reduced water use efficiency from 14.9 kg DM ha^{-1} mm^{-1} (five cycles of grazing) to 13.0 kg DM ha^{-1} mm^{-1} (three cycles of grazing) (Twerdoff et al., 1999b).

Soil Nutrient Status

The N benefits of forage legumes grown in the NGP have been documented by many workers over the past 75 yr (e.g., Badaruddin and Meyer, 1989; Hoyt and Leitch, 1983). Working in dry, subhumid southern Manitoba, Kelner et al. (1997) determined that net N additions of an alfalfa hay crop were 84, 148, and 137 kg ha^{-1} in the first, second, and third years of the stand, respectively. This suggests that relatively short-term alfalfa stands could maximize N input. Ferguson and Gorby (1971), on the other hand, recorded a slightly higher long-term N benefit between an 8- and 4-yr alfalfa stand. No similar study has been conducted in drier areas of the NGP.

Ferguson and Gorby (1971) reported that most N benefits from alfalfa or alfalfa–bromegrass stands to following grain crops occurred in the first 2 yr after forage termination. Hoyt and Leitch (1983) reported that N benefits from a number of different forage legumes occurred in the second and third year after forage termination. Both reported significant N benefits up to 7 yr after forage termination. Hoyt and Leitch (1983) determined that rotational N benefits to following grain crops were greatest for alfalfa > alsike clover > birdsfoot trefoil (*Lotus corniculatus* L.).

Forster (1998) attempted to separate N and non-N yield benefits from an alfalfa hay crop in Manitoba. He reported increased wheat yields (over the control) of 1100, 500, 200, 250, and 400 kg ha^{-1} due to N for the first five wheat crops after alfalfa, respectively, vs. yield increases of 200, 450, 400, 200, and 200 kg ha^{-1} due to non-N factors for the first five wheat crops after alfalfa, respectively. Therefore, after the second grain crop, rotational yield benefits from alfalfa were similar for N and non-N factors.

Several NGP researchers evaluated N benefits of single-year *dual purpose*—hay and late-season forage regrowth plowdown systems. Badaruddin and Meyer (1989) reported a fertilizer replacement value of legume (cut for hay and regrowth fall incorporated) equivalent to the addition of up to 150 kg N ha^{-1} on continuous wheat. Kelner and Vessey (1995) reported a net soil N contribution of 121 kg N ha^{-1} for 'Nitro' alfalfa in Manitoba. Working in Montana, Westcott et al. (1995) compared N contributions of single-year Nitro alfalfa and 'Bigbee' Berseem clover (*T. alexandrinun* L.). They concluded that, "if the goal in managing annual forage legume in a fall plowdown system is primarily for forage yield, then berseem clover in a two-harvest system may be preferable. If plowdown N-benefits are of greater priority, then Nitro alfalfa in a zero- or one-harvest system should be considered."

By adding N to the soil system, forages in rotation also decrease energy requirements for crop production. Effects of including alfalfa on energy use (Rice and Biederbeck, 1983, as cited in Campbell et al., 1990) and energy use efficiency (Hoeppner et al., 1999) have been documented for NGP cropping systems.

Forage legumes, especially in hay systems, remove large amounts of minerals from the soil (Woodhouse and Griffith, as cited in Heath et al., 1973). For example, in the long-term study (1958 to present) at Indian Head, SK, inorganic soil P levels were 37 kg ha^{-1} in continuous fertilized wheat, 27 kg ha^{-1} in continuous unfertilized wheat, and 21 kg ha^{-1} in the unfertilized forage-containing rotation (Campbell et al., 1993). In a southern Alberta study, including alfalfa-crested wheatgrass [*A. cristatum* (L.) Gaertn.] in a 6-yr forage–wheat rotation reduced the rate of soil N depletion but slightly increased the decline in exchangeable K levels (Pittman, 1977, as cited in Campbell et al., 1990). Forage legumes also affect soil chemical properties. For example, at the Breton plots, long-term use of forage legumes (1930 to present) has decreased the soil pH to the point where liming is critical to maintain crop production (Robertson, 1992).

Forage-based rotations that include pasture systems, where nutrients are recycled to the soil, are less nutrient exhausting that hay systems. This may be particularly so in the moister, northern area of the NGP. In a short-term rotational pasture study over four years in the Alberta parkland, where annual and perennial species were compared at three grazing intensities, soil-C in the surface 0–5 cm (Typic Haplustall silt loam) increased for perennial grasses, but decreased for annuals and was unaffected by grazing intensity; total-N and C:N ratio were unaffected by species or grazing intensity (Mapfumo et al., 2000). However, the mineral-N fraction was much more dynamic and responsive to grazing intensity. Very intensive grazing (five cycles of grazing) resulted in soil mineral-N levels exceeding 200 kg N ha^{-1} compared to 95 kg N ha^{-1} (0 to 60 cm depth) for less intensive grazing (three cycles of grazing) averaged over annual and perennial species (Baron et al., 2002). Nuttall et al. (1980) reported that economic returns from fertilizing mixed alfalfa-grass pastures was maximized at 90 kg N

ha^{-1} and 20 kg P ha^{-1} when the stocking rate was 3.7 head ha^{-1}. In the same study, herbage yields increased with N applications up to 185 kg N ha^{-1}, but NO_3-N accumulated in the 30 to 60 cm depth of the soil profile. In the drier areas, and perhaps on long-term grassland, little mineral-N remains in the soil solution at any time. Soil micro-organisms are much less active when soil available water content is low (Biederbeck et al., 1984), and even in moist periods, immobilization of mineralized-N by soil microflora predominates mineralization of organic matter (Woodmansee et al., 1981). In the drier areas, little fertilizer-N is applied to pastures and grazing is mostly of an extensive nature. Because differences for nutrient dynamics exist between short-term and long-term sequences, moist and dry, and intensive vs. extensive grazing regimes, more research is needed on impacts of nutrient cycling as well as fertilizer requirements for pastures in the NGP.

Soil Quality

Many non-N benefits of forage in a crop rotation are attributed to improved soil quality. This is especially important given that NGP soils have undergone serious degradation since the early part of the 20th century (McGill et al., 1981). Many improvements in soil physical condition by forage have been attributed to greater soil C in forage-based compared with annual crop systems (e.g., Spratt, 1966). Pavlychenko (1942) reported a much higher proportion of large soil aggregates for various introduced and native perennial grass species than for a wheat–oat (*Avena sativa* L.) rotation, but "at depths exceeding 10 cm, none of the cultivated grasses had an appreciable effect upon the soil structure." Native grass species such as Porcupine grass (*Stipa spartea* Trin.) and blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Stead] improved soil structure between 10- and 60-cm soil depth more than the very popular crested wheatgrass (Pavlychenko, 1942).

From a management perspective, perennial pastures provide a large litter base and root system that promotes greater storage of C in the soil compared with annuals. In short-term pasture sequences in the moister NGP, Baron et al. (2002) estimated that total C contribution (roots and litter) for perennials was 2.7 times more than for annuals; contribution of roots and litter was 1.5 times greater with light compared with heavy grazing.

McGill et al. (1986) studied the dynamics of soil microbial C and N in two systems in the Breton plots: wheat–fallow and wheat–oat–barley (*Hordeum vulgare* L.)–forage–forage. They found that the 5-yr rotation contained 38% more N and 117% more microbial N than did the wheat–fallow system. In addition to increasing long-term soil biological fertility, N additions to NGP soils are also known to increase soil aggregation (Biederbeck et al., 1984). Therefore, both the C and N additions from forages reduce soil erosion potential of NGP soils. Working in the semiarid zone of the NGP, Naeth et al. (1991) reported that high soil microbial populations associated with pasture grass rhizospheres produce polysaccharide mucigels that promote aggregation in the short term while in the long term, the buildup of humic materials will stabilize aggregates. On a sandy soil in southern Manitoba, Banjeree et al. (2000) observed a reduction in soil microbial biomass C when predominantly alfalfa pastures were grazed at heavy compared with light stocking rates (i.e., 2.2 vs. 1.1 steers ha^{-1}). Cultivation of long-term prairie reduces soil biomass C as well as concentrations of soluble sugars and amino N (Deluca and Keeney, 1994).

Cavers (1996) reported that a 4-yr alfalfa hay crop resulted in saturated soil hydraulic conductivity 10 times higher than in a small-grain rotation on a clay soil in Manitoba; this difference was measured at 25-, 50-, and 75-cm soil depths. Wheat root activity on these same plots was found to be significantly deeper after alfalfa compared with an annual crop rotation (Forster, 1998).

Some suggest that intensive rotational grazing may increase water infiltration (e.g., Savory, 1988). Mapfumo et al. (1999) questioned this assertion because soil pressures from animal hooves can be as much as 200 kPa, which is considerably greater than the pressure exerted on the soil by a tractor (30–50 kPa) (Profitt et al., 1993). However, in an Alberta study comparing intensive vs. extensive grazing of annual and perennial forages, Mapfuno et al. (1999) found only a few negative effects of intensive grazing on soil physical properties and suggested that, "natural processes such as freeze-thaw action, wet-dry cycles, and earthworm activity likely reduced the effects of animal trampling." In fact, their evidence suggests that extensive grazing causes soil compaction and restricts soil water movement. On this excellent loamy soil, bulk density increased in a curvilinear fashion with increasing exposure to animal traffic but increased faster for annual than perennial pastures (Twerdoff et al., 1999a). However, it was concluded that intensive rotational grazing systems may not cause serious compaction problems for soils of this type.

Pests

Weed suppression with forages, especially perennial hay crops, has been documented in various NGP studies over the past 50 yr. Siemens (1963) described results of a long-term crop rotation study at Brandon, MB where wild oat (*Av. fatua* L.) *dockage* (i.e., percent of yield consisting of wild oat seeds) in grain crops averaged <1% in forage-containing rotations and 15% in continuous grain or fallow–grain systems. In a survey of Canadian prairie farmers, 83% of respondents reported fewer weeds after alfalfa vs. grain rotations, with good suppression of wild oat, green foxtail [*Setaria viridis* (L.) Beauv.], and Canada thistle [*Cirsium arvense* (L.) Scop.] (Entz et al., 1995). Ominski et al. (1999) reported that wheat after perennial alfalfa or alfalfa–grass hay crops had significantly fewer problem weeds than wheat in annual grain rotations and that forage in the rotation shifted the weed community composition away from wild oat, green foxtail, and Canada thistle. Alfalfa did, however, select for dandelion (*Traxacum officianale* Weber in Wiggers).

Schoofs and Entz (2000) found that even single-year forage crops provide significant weed control benefits. These workers concluded that, "the ideal annual forage system for weed management should combine the early season vigour of a biennial crop, the continuous competition of a long-season crop, and the intense mid-summer competition of a C_4 crop. Therefore, a combination of two, or possibly more crops grown together, may be required." Harker et al. (2000) studied the impact of grazing intensity on weed populations in perennial and annual pastures. They found that dandelion increased with increasing grazing intensity and years of grazing in perennial grass pastures at a rate of 4 plants m^{-2} for every unit increase in intensity (three to five cycles of grazing); annual weeds, mostly shepard's purse [*Capsella bursa-pastoris* (L.) Medikus], increased at a rate of 51 plants m^{-2} for each unit increase in grazing intensity. However, in annual pastures, where tillage was a factor, shepard's purse was higher at low vs. high grazing intensities; high grazing intensity served to reduce annual weed populations.

Fewer studies have considered forage effects of plant diseases or insects. It is important to recognize that perennial forages are sometimes continuous monoculture; therefore, pathogen or insect pest populations can build up in the crop [e.g., *Sclerotinia sclerotiorum*—both alfalfa and canola (*Brassica* spp.) are suceptible]. By the same token, a perennial forage stand provides a long period for pathogens to decline, thereby reducing damage to a following susceptible crop. Both Penning and Orr (1988) and Tinline (as cited in Campbell et al., 1990) reported that the only rotation to effectively reduce inoculum of common root rot (*Cochiablus sativus*) was a 3-yr forage hay stand.

Economic Benefits

The most comprehensive economic analysis of forage-based cropping systems has been conducted by Zentner and coworkers (Agriculture and Agri-Food Canada, Semiarid Prairie Agriculture Research Centre). Using information from long-term crop rotation studies at Indian Head, Scott, and Melfort, SK, they determined input costs, net returns, and income variability associated with forage-based and annual grain crop–based rotations (Zentner et al., 1986). Cost of production for forage-based systems was lower than for continuous grain production but higher than a wheat–fallow system. Net returns tended to be more stable across a range of crop prices for the forage-based systems than for annual systems. Including 2- or 3-yr forage crops in a 6-yr rotation was found to significantly reduce income variability or risk. At both locations, adding a 2- or 3-yr forage phase into the 6-yr crop rotation decreased income variability significantly more than crop insurance. Therefore, to reduce risk, a biological solution appeared to be superior to a government program.

Agronomists and farmers are interested in knowing the minimum length of a forage hay crop that is economically optimal. This question was partially addressed by Zentner et al. (1986), who reported that 2- or 3-yr forage stands in a 6-yr rotation are economical. Other NGP research suggests that alfalfa and other forage legume monocultures should be terminated after 4 or 5 yr for maximum economic efficiency of the rotation (Jeffrey et al., 1993). Most forage stands in dryland regions are currently maintained for at least 7 yr (Entz et al., 1995).

Environmental Benefits

Reduced Nitrate Leaching

Perennial forages can scavenge nutrients from greater soil depths than annual crops because of their deep root systems (Pavlychenko, 1942). In the long-term study at Indian Head, SK, Campbell et al. (1994) found that a 3-yr alfalfa–bromegrass crop in a 6-yr crop rotation reduced buildup of subsoil (to 240 cm) NO_3. Entz et al. (2001a) observed NO_3 extraction to depths of 90, 180, 210, and 270 cm in the first 4 yr of an alfalfa stand, respectively. Working on the same trial, Kelner et al. (1997) determined that this high subsoil NO_3 did not reduce N fixation of alfalfa in Years 1, 2, or 3 of the stand.

Campbell et al. (1994) reported significant NO_3 leaching from alfalfa in the Indian Head rotation. They attributed this observation to the fact that, in the Indian Head study, alfalfa is followed by a year of fallow. Under these conditions, legumes increased soil N supply, but the net downward movement of water during the fallow year resulted in NO_3 leaching. Using no-till vs. tillage methods to terminate alfalfa crops improves the synchrony of N release from alfalfa and uptake by following cereal grain crops, thereby reducing the risk of NO_3 leaching from perennial alfalfa (Mohr et al., 1999). The role of perennial forages to extract deep-leached NO_3 is becoming more important as large-scale livestock production increases in the NGP region.

Provide Critical Wildlife Habitat

Forage crops play an increasingly important role in providing critical habitat for many species, including migrating waterfowl. These programs have increased in sophistication over time; they have evolved from simply establishing perennial forage crops to use of locally adapted native grass species, often in a sculpted seeding system (Jacobson et al., 1994). Development of native plant materials and ecotypes for multiple land-use systems has been in place in the USA for some time (e.g., USDA at Mandan, ND; J. Berdahl, personal communication, 2000). In Canada, Ducks Unlimited Canada in cooperation with Agriculture and Agri-Food Canada and university scientists have recently initiated a program to develop ecological varieties of approximately 20 native grass species, 7 forbs, and 4 shrubs (B. Wark, personal communication, 1998).

Carbon Sequestration in Soils

The potential to sequester atmospheric CO_2 as soil organic C in forage-based cropping systems is well recognized (Spratt, 1966). Carbon sequestration in cropland seeded to perennial grasses averaged 1.1 Mg C ha^{-1} yr^{-1} over a 5-yr period in a survey of land under the Conservation Reserve Program in the USA (Gebhardt et al., 1994). Because of their deeper root systems, perennial forage plants can place C deeper into the soil system than annual plants, resulting in better long-term C storage. Some previous studies in the NGP region have focused on long-term effects of fertilization on long-term C storage (e.g., Nyborg et al., 1999; Cihacek and Meyer, 2000). As Baron et al. (2002) pointed out, perennial forage systems result in greater soil C accumulation than annual forage systems.

NEW OPPORTUNITIES TO DIVERSIFY CROP ROTATIONS WITH FORAGES

Intensification of Forage-Based Crop Rotations

Cultivated forages are sown on 5 to 15% of the arable landbase in the NGP region. Hence, only a small percentage of the landbase can receive the benefits of forages at any one time. Because the total forage acreage (especially perennial forages) is not likely to increase dramatically in the future, the best approach for increasing exposure of arable lands to forage benefits is to cycle forages through the crop rotation more quickly.

While the minimum alfalfa stand lengths to achieve weed control (Ominski et al., 1999), N (Kelner et al., 1997), subsoil NO_3 extraction (Entz et al., 2001a), and economic (Jeffrey et al., 1993) benefits are 5 yr or less, forage stand length is currently over 7 yr in the region (Entz et al., 1995). Therefore, the potential exists to use the existing forage hectarage more efficiently by shortening forage stand length and moving forages from field to field more rapidly. However, farmers are reluctant to terminate forage stands for two main reasons: difficulties encountered when establishing and terminating forage stands (Entz et al., 1995).

No-Till to Enhance Cycling Forages in a Rotation

Forage seedlings are especially vulnerable to soil moisture deficits because the small seeds are sown near the soil surface. Conventional seedbed preparation techniques result in dry seedbeds and increase the risk of soil erosion. No-till forage establishment increases soil water available to germinating forage seeds and increases establishment success, especially when postseeding precipitation is absent (Allen and Entz, 1994). The long-term crop rotation study at Indian Head, SK is now conducted under no-till, and since this change, alfalfa–bromegrass establishment has improved greatly (Lafond, personal communication, 1999).

Most forages in the NGP are seeded with a companion crop (Entz et al., 1995). Companion crops tend to reduce forage establishment and reduce first-year forage yields and sometimes even second-year forage yields (Smith et al., 1997). However, despite the loss in forage yield potential from companion crops, most workers agree that use of companion crops is economical. For example, working in Alberta, Smith et al. (1997) concluded that companion crops for alfalfa establishment significantly enhanced economic performance over 3 yr compared with where no companion crop was used, especially when the companion crop was removed early (as silage). Jefferson and Zentner (1994) concluded that forage yield would have to be negatively affected by companion crops for 2 yr after forage establishment to be less profitable than establishment without a companion crop.

It is useful to note that many of the establishment-year benefits of companion crops can be achieved with no-till forage seeding (i.e., reduced blowing soil damage, shading, and lower soil temperatures) without the competition for resources, especially water (Allen and Entz, 1994). Smith et al. (1997) concluded that herbicides are not economically feasible during the forage establishment year.

Most producers currently use some tillage to terminate forage stands (Entz et al., 1995). This represents a significant investment of time and machinery. Use of herbicides instead of tillage to terminate alfalfa is feasible (Bullied et al., 1999) and has been shown to increase soil water conservation and grain yields in following crops (Bullied and Entz, 1999). No-till seeding of winter cereals into herbicide-killed forages (Entz and Bamford, unpublished data, 2000) has the advantage that winter cereals use the limited water supply more efficiently than spring cereals (Gan et al., 2000). Other benefits of no-till alfalfa termination include fewer weeds in subsequent crops due to less soil disturbance (Ominski and Entz, 2001).

Expanded Role for Annual Forages

Annual forages play an important role in the feed supply. In addition to supplying winter feed (e.g., silage), annual forages are being promoted as a means to extending the length of the grazing season, a very important goal for livestock producers.

Traditional annual forage species in the NGP region include barley, oat, fall rye (*Secale cereale* L.), and wheat (Kilcher and Heinrichs, 1961). For example, barley for silage is the choice of the feedlot industry in southern Alberta (MacAlpine et al., 1997). Triticale (× *Triticosecale* Wittmack) is a newer cereal that has outperformed traditional cereals in the semiarid regions of western Canada (McLeod et al., 1998) and Montana (Stallknecht and Wichman, 1998). Other novel annual species, such as sunflower (*Helianthus annuus* L.), canola, corn, and pulses, have been previously tested for forage potential (Berkenkamp and Meeres, 1987). Annual forage mixtures, while typically not enhancing yield (Baron et al., 1992), can enhance quality (Carr et al., 1998) and can greatly improve seasonal DM distribution (Baron et al., 1992; Carr et al., 1998; Manske and Nelson, 1995).

It is generally accepted that perennial pastures are the least expensive feed sources for the beef cow herd. However, novel annual forage systems can fill a void at specific points in the livestock enterprise, resulting in significant savings for the entire enterprise. Motivation for novel pasture systems stem from the fact that (i) conventional pasture system, while low cost, cannot keep up with the demands of cows, calves, or stocker cattle, all of which are gaining in size and weight; (ii) it is less expensive to overwinter beef cows conventionally if they enter the winter feeding period in good body condition (Willms et al., 1993); and (iii) it is cheapest to feed some classes of livestock (e.g., beef cattle) on pasture than in dry lots (Adams et al., 1994). Manske and Nelson (1995), working in western North Dakota, reported that oat–pea (*Pisum sativum* L.) intercrops, millet (*Panicum* spp.), and fall rye worked well in annual grazing systems. Novel systems aimed at improving seasonal forage DM distribution have also been developed. Mixtures of spring and winter cereals, for example, provide earlier grazing than winter cereals alone but continue producing DM later in the season compared with spring cereals planted alone (Baron et al., 1993a, 1993b). Mixtures of winter cereals and Italian ryegrass (*Lolium multiflorum* L.) respond similarly to winter–spring cereal mixtures (Thompson et al., 1992). A novel system for late-season and winter grazing is swath grazing. Cereals are swathed from heading until dough stage, and animals graze the swaths. A wide range of C_3 and C_4 cereal crops are being tested for use in swath grazing (McCaughey, unpublished data, 1999). Cereals for swath grazing are sown later in spring—a proven tactic to reduce wild oat populations (Schoofs and Entz, 2000).

Low-cost cereal straw and chaff represent a vast potential feed source for gestating beef cows across the NGP (Coxworth et al., 1981). In Alberta, MacAlpine et al. (1997) estimated that 1.2 t of straw or 2.2 t of chaff are required to winter (200 d) a 450-kg cow. Oat and barley straw are generally considered to have a higher feeding value than triticale and wheat straw (Coxworth et al., 1981; Wedin and Klopfenstein, 1995).

Coxworth et al. (1981) reviewed straw and chaff management for the dry part of the Canadian NGP. They observed that stage of maturity and N fertilizer application could have significant effects on nutritive value of wheat straw, but location could have a greater effect. They noted differences among wheat cultivars for feeding value, that chaff had greater feeding value than straw, and that NH_3 application could have substantial positive impacts on straw and chaff nutritive value. Whether ammoniation of straw and chaff is economical depends on relative costs of anhydrous NH_3 and alternative feedstuffs, such as cereal grains.

Agronomic benefits of chaff collection include residue management and weed and volunteer crop control. High chaff yields in moist areas pose a limitation to direct seeding. Weed control benefits of chaff collection were identified by Shirtliffe (1999), who determined that wild oat and green foxtail patch dispersal was virtually eliminated when chaff was collected. This is another example of how integrating livestock and grain production provides important synergy within the farming system.

Adding Value to Beef and Dairy Products

Besides representing over 90% of the beef cow ration, additional benefits may be derived from increasing forage content in rations of higher-performing ruminants. These benefits may be economical, as in low-cost rations for beef production and in new health-related markets for beef and dairy products. Ultimately, new ways to divert land out of grain production may result. The extent to which this impacts beef and dairy industries, beyond niche markets, remains to be seen. Backgrounding beef on predominately forage rations, often pasture, before entry into the feedlot system, by growing animals at relatively low rates of gain is a means of providing a low-cost animal to the feedlot system. This part of the beef system is predicated on forage or pasture being a low-cost feedstuff (Mathison, 1993). It is also a means for placing beef animals into a specific temporal market in the feedlot-packing system. Profitability depends on supply and demand characteristics of both beef and grain markets.

Pasture finishing of beef cattle may be a viable option to some producers. The immediate advantage of pasture finishing is the potential of relatively low cost of beef production although this must be weighed against cost of grain during times of low grain prices and certain supply–demand relationships for beef markets as in backgrounding. Research in Canada and the USA since the 1950s has shown that pasture-finished beef is feasible although results from research has been mixed (Aalhus and Mandell, 1999). Problems with meat quality and consumer acceptance of pasture-finished beef, such as off-flavor (Mandell et al., 1998) and discolored fat (Aalhus and Mandell, 1999), have occurred. However, some traits are confounded with respect to age of cattle and fat cover when forage vs. grain-finished beef are compared (Mandell et al., 1998). McCaughey and Cliplef (1995) demonstrated that about 70% of cattle finished on high quality pasture would meet standards for finished beef on the Canadian grading system. This appears typical. The remaining 30% finished after relatively short periods (30–75 d) on a high grain ration. Pasture-finished beef in this trial met standards for fat color and was acceptable in taste panel studies for tenderness and flavor. The challenge for pasture-finished beef is to produce a consistent and economical meat product. A window of opportunity is available to those producers who can market a specialized product.

Other niche markets may develop for forage or predominately forage-finished beef on the basis of enhanced human health. Forage-based rations are linked with relatively high concentrations of conjugated linoleic acid (CLA) and omega-3 fatty acids in meat (Aalhus and Mandell, 1999) and dairy products (Jiang et al., 1996). Meat and dairy products may contain 1 to 2% CLA. Health benefits derived from CLA include anticarcinogenic, anticachexic, and antiatherosclerotic properties (Aalhus and Mandell, 1999). Omega-3 fatty acids, also found in fish meal (Mandell et al., 1997) and including linolenic, eicosapentaeoic, and docosahexaenoic acids, are enriched in meat from forage-finished rations (Aalhus and Mandell, 1999). While omega-3 fatty acids appear to have a role in prevention of many age-related diseases, their role in mitigation of coronary heart disease has been most extensively studied and verified (Addis and Romans, 1989). In the future, forage-fed dairy and pasture-finished beef may have a role in niche markets for a health conscious and aging society in

North America. More research is required to further elucidate these relationships.

Alfalfa in Grazing Systems

Although NGP producers have long included alfalfa as a minor component (e.g., 5–15%) of cultivated pastures, over the last 10 yr, there has been a threefold increase in pasture hectarage where alfalfa is the primary component (Smith and Singh, 2000). Twelve to 15% of alfalfa stands are currently grazed on a regular basis or at some point in the life of the stand (W. Thompson and G.D. Lacefield, personal communication, 1998).

Alfalfa provides the perfect combination of high forage digestibility and protein for pasture-based finishing systems. Popp et al. (2000) reviewed animal performance of alfalfa-based and grass pasture systems. With proper grazing management, yearling steers can gain as much as 1.5 kg head^{-1} day^{-1}. Reported daily steer gains in pure orchardgrass (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* L.) range from 0.69 to 0.79 kg head^{-1}. Animal rate of gain is improved in alfalfa–grass pastures when alfalfa contributes as little as 35% to the sward.

Although alfalfa offers tremendous productivity benefits, there are two reasons that it has not been traditionally used for pasture: poor persistence (Smith et al., 2000) and bloat (Popp et al., 2000). Progress is being made in controlling bloat by developing bloat-reducing cultivars (Coulman et al., 2000) and through management strategies, chemical feed additives, and other treatments (Berg et al., 2000). Tremendous progress has also been made in breeding cultivars that are grazing persistent (Smith et al., 2000). Cultivars with a high percentage of the alfalfa subspecies *falcata* offer potential to combine excellent winter survival and grazing survival (Berdahl et al., 1986; Smith et al., 2000).

Any efforts to increase the portion of beef cattle diet from pasturing would increase the amount of forage grown in rotation, thereby increasing rotational benefits from forage described earlier.

Novel Grain–Forage–Livestock Systems

A novel forage-based cropping system has been used successfully for decades in Australia (Grace et al., 1995). Here, self-regenerating subterranean clover (*T. subterraneum* L.) and annual medic (*Medicago* spp.) are grown in pasture–grain systems. There has been considerable interest in adapting these systems to the NGP region. Sims and Slinkard (1991) concluded that black medic (*M. lupulina* L.) had potential for replacing summer fallow in a wheat–fallow cropping system in Montana. Long-term field trials demonstrated that ‘George’ black medic (Sims et al., 1985) successfully reseeded itself and boosted wheat yields by 1300 kg ha^{-1} compared with wheat on summer fallow. In this system, black medic can be grazed during the fallow year.

Self-regenerating annual medics can also be integrated into continuous grain production systems. Three annual medic species were established on 40 ha on a North Dakota farm in 1991. The medics have been regenerating successfully in a continuous cropping system for the past 8 yr (K. Aldridge, personal communication, 1998). They provide significant forage for late-season grazing, as well as weed suppression, plus they produce enough seed to successfully re-establish themselves each year. Thiessen-Martens and Entz (2001) determined that a large area of the NGP has sufficient heat and water resources for late-season growth, including seed production of several medic and subclover species. Selection of suitable medic species and management practices is currently underway (Entz and Carr, unpublished data, 2000).

Forages in Organic Systems

Organic farmers are well aware of the importance of forages in organic cropping systems. A survey of organic farms in Manitoba, Saskatchewan, and North Dakota showed that 30 to 40% of the landbase on organic farms was seeded to alfalfa or other perennial forages at any one time (Entz et al., 2001b). Interestingly, forage hay yields on organic farms were higher, on average, than on area conventional farms, suggesting that organic farmers pay close attention to forage management.

Three long-term crop rotation studies have been established in the past decade to evaluate the role of forages in organic crop production systems: the Glenlea long-term crop rotation study at the University of Manitoba and Agriculture and Agri-Food Canada studies at Scott, SK, and Lethbridge, AB. Results of the longest running of these studies (Glenlea, established in 1992) indicate that inclusion of a 2-yr alfalfa hay crop in a 4-yr rotation is critical to successful organic flax production. For example, in a 4-yr wheat–pea–wheat–flax rotation, after two full rotation cycles, the flax yielded 1691 kg ha^{-1} with full inputs (herbicides and fertilizers) and 777 kg ha^{-1} under organic conditions. In the 4-yr wheat–alfalfa–alfalfa–flax rotation, flax yielded 1577 kg ha^{-1} with full inputs and 1371 kg ha^{-1} under organic conditions (Entz, unpublished data, 1999). These data underscore the importance of integrated (i.e., forage–grain) cropping systems for successful organic crop production.

FUTURE RESEARCH CHALLENGES

Almost all aspects of forage production require further research. One challenge is crop development. Because there are so many different plant species involved in NGP forage systems, maintaining breeding and selection programs for all of them is difficult. In the past, the majority of breeding efforts have involved alfalfa, with grasses receiving much less attention. Also, annual crops that fill feed gaps at critical periods during the grazing season need attention from both plant breeders and agronomists. Research to adapt novel forage systems like the self-regenerating annual legumes to the NGP also deserves more attention.

Few trials of cropping systems currently underway in the NGP include forages. In western Canada alone, dozens of short-, medium-, and long-term cropping system studies were established in the past decade to consider interactions among tillage system, crop rotation, and pest management. The vast majority of these studies include only grain crops. At the same time, many of the long-term *classical* trials, which include forages in the system, are being discontinued due to budget constraints. Without proper documentation of forage benefits in contemporary cropping systems, it will become increasingly difficult for agronomists to visualize the potential of forages to diversify NGP cropping systems.

Nutrient cycling is very different in pasture vs. hay systems. However, little attention has been paid to this area of study. Also, the impacts of nutrient cycling on intensive pasture in moist areas is different than for dry areas, just as long-term vs. short-term grasslands differ, and legumes and grasses differ. Fortunately, several new forage-based cropping systems that include pasturing livestock in the system have recently been initiated in semiarid (Dickinson and Mandan, ND) and subhumid (Lacombe, AB and Brandon, MB) regions of the NGP.

There is a great need to investigate the role of forages at the systems level where all, or at least several, components of the soil–crop–livestock system are considered together. When recommendations are made at the systems level, optimization of the whole system is emphasized, not necessarily maximization of all parts. Taken alone, the forage component is often less valuable; however, its presence in a cropping system provides great stability and profitability to the whole system.

Finally, because the benefits of forages in cropping systems are sometimes subtle and do not manifest themselves immediately, forage-based cropping systems research needs to be conducted over the long term. From literature cited in this review, it is clear that without long-term, field-based research, we would know much less about the potential to diversify NGP cropping systems with forages. Perhaps the greatest research need, therefore, is to maintain long-term, field-based forage research programs and establish new programs that address new questions.

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