Integrating green manure and grazing systems: A review

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Thiessen Martens, J. R. and Entz, M. H. 2011. **Integrating green manure and grazing systems: A review**. Can. J. Plant Sci. **91**: 811–824. Green manuring, also referred to as cover cropping, is an ancient practice that is gaining popularity, especially in ecologically integrated farming systems. Much green manure research in Canada has focused on legumes, where green manure plant material is incorporated into soil. This review focuses on the role of livestock in utilizing traditional and novel green manure crops adapted to the Canadian prairies. Legume and non-legume green manure plant species are discussed in terms of suitability to grazing management by different livestock species. Integrating grazing livestock into green manure systems affects nutrient cycling and potential nitrogen (N) loss pathways. However, losses may not be substantially different from other production systems, especially when loss mitigation practices are employed. Grazing green manures may also affect soil biological and physical properties. We conclude that grazing green manures may provide economic as well as biological advantages over the traditional approach of soil incorporation. For example, a green manure biomass yield of 5000 kg ha^{-1} is sufficient to produce 175 kg ha^{-1} of animal live weight gain, providing a gross revenue of \$385 to \$770 ha^{-1} at April 2011 prices, while returning at least 75% of N and other nutrients to the field. Barriers to farmer adoption of grazed green manure systems include a lack of livestock management knowledge and infrastructure.

Key words: Green manure, grazing, crop-livestock integration, organic farming, cover crops, nitrogen benefits

Thiessen Martens, J. R. et Entz, M. H. 2011. **Intégration de l'engrais vert aux régimes de paissance : panorama**. Can. J. Plant Sci. **91**: 811–824. L'engrais vert, également appelé « culture-abri », est une pratique ancienne qui gagne en popularité, principalement dans les systèmes agricoles intégrés qui misent sur l'écologie. Une grande partie des recherches sur les engrais verts poursuivies au Canada porte sur les légumineuses, que l'on incorpore ensuite au sol. La présente analyse bibliographique se concentre sur le rôle du bétail dans l'exploitation des engrais verts classiques et nouveaux, adaptés au climat des Prairies canadiennes. Il y est question des engrais verts de légumineuses ou pas et de leur convenance pour la paissance de diverses espèces animales d'élevage. L'intégration de la paissance à la culture des engrais verts affecte le cycle des éléments nutritifs et les pertes potentielles d'azote (N). Cependant, ces pertes pourraient ne pas sensiblement différer de celles observées avec d'autres systèmes de production, en particulier lorsqu'on recourt à des mesures d'atténuation. La paissance sur engrais vert pourrait aussi affecter les propriétés biologiques et physiques du sol. Les auteurs concluent que faire brouter les engrais verts aux animaux pourrait présenter des avantages économiques et biologiques, comparativement à l'approche classique qu'est l'incorporation au sol. Ainsi, un rendement en biomasse de 5000 kg d'engrais vert par hectare suffirait à produire 175 kg de gain de poids vif par hectare chez les animaux, pour un revenu brut de 385 à 770 \$ par hectare aux prix d'avril 2011, tout en restituant au moins 75 % du N et des autres éléments nutritifs au sol. Le manque de connaissances en élevage et des infrastructures insuffisantes empêchent les agriculteurs d'adopter la pratique de la paissance sur engrais vert.

Mots clés: Engrais vert, paissance, intégration des productions végétales et animales, agriculture biologique, culture-abri, avantages pour l'azote

Integrating legume cover crops or green manures into annual crop rotations has the potential to offer substantial benefits to Canadian prairie cropping systems. The benefits of cover crops and legume green manure crops are well documented and include nitrogen (N) fixation, soil conservation, improvements in soil organic matter and soil structure, and weed control, among others (Gardner and Faulkner 1991; Hartwig and Ammon 2002). The challenge facing Canadian prairie farmers is to find appropriate niches for cover crops in the short growing season of this region. A second challenge is to make these cover crops economically feasible.

Biological N fixation (BNF) is one of the main benefits of planting legume green manures or cover crops (Hartwig and Ammon 2002). Nitrogen management is a primary concern for farmers since N is the nutrient required in greatest quantities by most crops and is also lost from the system easily. Historically, BNF by *Rhizobium* and other bacteria in association with legumes provided most of the N required in cropping systems. Since the invention of the Haber-Bosch process in the early 20th century, use of synthetic nitrogen fertilizers has become widespread. In 2006, N fertilizer retail sales in Canada were 1.54 million

Abbreviations: BNF, biological N fixation; **CP**, crude protein; **DCD**, dicyandiamide; **DM**, dry matter; **LWG**, live weight gain; **ODAP**, β-N-oxalyl-l-α, β-diaminopropionic acid tonnes (Canadian Fertilizer Institute 2007). World demand for fertilizer N was 103.9 million tonnes in 2010 and is projected at 111.6 million tonnes for 2014 (Food and Agriculture Organization of the United Nations 2010).

While organic farmers use BNF out of necessity, the use of legumes for N supply is not as common among conventional farmers, especially those who do not produce livestock and have no forage requirements on the farm. The use of green manure crops for N supply is rarely practiced on conventional farms in short growing season areas since it requires taking a field out of cash crop production for one growing season and receiving no income from that land in that year. Even though there is a direct N benefit to the following crop, growing annual legume green manure crops is generally not seen as an economically viable option by conventional farmers. The lack of income during the green manure year also poses an economic challenge for organic producers.

Improved economics of legume green manure crops could increase adoption of this practice in both organic and conventional production. One approach for obtaining immediate value from a cover crop or green manure is to integrate grazing livestock into the system (Gardner and Faulkner 1991; Sulc and Tracy 2007). Integrating crop and livestock production systems can increase income and reduce income variability (Anderson and Schatz 2003; Franzluebbers and Stuedemann 2007; Russelle et al. 2007) and may also increase the efficiency of resource use in agroecosystems (Wilkins 2008).

Grazed green manure systems are similar in concept to the traditional ley farming systems of northern Europe, in which 2–3 yr stands of grazed forage crops are rotated with grain crops, and to the Australian wheat (*Triticum aestivum* L.)–sheep system, in which self-regenerating forage legumes are included in rotation with wheat and grazed by sheep. The wheat-sheep system is credited with increasing the productivity of both crop and livestock systems, as well as reducing dependence on external N inputs and improving soil structure and crop water-use efficiency (Gardner and Faulkner 1991). Grazed cover crop systems are being explored in various locations in the United States of America, with evidence of similar benefits (e.g., Krall et al. 2002; Franzluebbers and Stuedemann 2007, 2008). These benefits may also be realized in the cropping systems of prairie Canada by integrating grazing livestock into legume green manure systems.

Little information exists on grazed green manure systems in short growing season areas such as the Canadian prairies. Major questions include the effect of grazing on nutrient cycling, animal productivity in such a system, and the grazing management (including labour and infrastructure) required to operate the system. In this paper, we examine the potential of grazed green manure systems as an economically and ecologically viable option for BNF on both conventional and organic farms in western Canada.

FEASIBILITY OF GRAZED GREEN MANURE SYSTEMS

The feasibility of integrating green manure crops and grazing systems depends on both the plant and animal aspects of the system, as well as any interaction between these aspects. This includes green manure productivity, forage quality parameters, adaptation of green manures to grazing and animal performance in such a system. In this review, we focus on the plant-related components of the system and the interactions between plant and animal.

Green Manure Productivity

A variety of annual legumes are commonly grown as green manure crops in the prairie provinces, including field pea (*Pisum sativum* L.), black lentil (*Lens culinaris* Medikus) and chickling vetch (*Lathyrus sativus* L.), as well as sweet clover (*Melilotus officinalis* L.), which is a biennial. Other less common annual green manure species include fababean (*Vicia faba* L.), hairy vetch (*Vicia villosa* Roth ssp. *villosa*), woolypod vetch (*Vicia villosa* Roth ssp. *varia*), Tangier flatpea (*Lathyrus tingitanus* L.), annual medics (*Medicago* spp.) and berseem clover (*Trifolium alexandrinum* L.). Perennial forage species such as alfalfa (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.) can also be grown as single-year stands and treated as annual green manures (Bullied et al. 2002).

Under typical growing conditions in the Black soil zone, annual legume green manures can generally produce 5000 kg ha^{-1} of dry matter (DM). In drier regions such as the Brown soil zone, annual green manure biomass production could generally be expected to reach 2500 kg ha^{-1}. McCartney and Fraser (2010) report DM yields of 3.5–12.6 Mg ha^{-1} for various annual green manure legumes under rainfed conditions in the Black soil zone of Saskatchewan and Alberta, and 1.6–7.2 Mg ha^{-1} in the Brown soil zone. Similar results have been obtained by Zentner et al. (2004) at Swift Current SK and Bullied et al. (2002) at Winnipeg MB.

Legume green manure crops generally obtain about 40–80% of their N requirements through fixation (Sarrantonio 1998), which subsequently becomes available to other crops. The quantity of N supplied by a green manure crop depends on the DM production by the legume, the concentration of N in the plant material, and the proportion of N obtained by fixation rather than by uptake from the soil. Sarrantonio (1998) suggests that the N contained in the above-ground portion of the plant is roughly equivalent to the amount of N fixed. The N concentration of legumes is typically between 25 (Peoples et al. 2001) and 30 g kg^{-1} DM (Zentner et al. 2004). With typical green manure DM yields of 2500 and 5000 kg ha^{-1}, for the Brown and Black soil zones, respectively, N contribution to the system would be 63 to 75 kg ha^{-1} for the Brown soil zone and 125 to150 kg ha^{-1} for the Black soil zone, assuming that none is lost from the system. Badaruddin and Meyer (1990) found that a legume green manure crop provided 150 kg ha^{-1} of N to a subsequent wheat crop in North Dakota and Bullied et al. (2002) observed a 51–92 kg ha^{-1} increase in N uptake by cereals following a legume green manure compared with cereals following canola. An N contribution of this size is sufficient to support one or more grain crops after the green manure year.

Suitability of Green Manures for Grazing

The suitability of annual legume green manure crops depends partly on DM production, but other factors, such as forage quality parameters, palatability, adaptation to grazing and anti-nutritional or toxic effects, must also be considered. Based on these characteristics, many annual green manure legumes, such as hairy vetch, cowpea (*Vigna unguiculata* L), field pea, medics, and subterranean clover (*Trifolium subterraneum* L.) are considered ''good'' or ''very good'' for grazing [Sustainable Agriculture Network (SAN) 1998].

The forage nutritive value of annual legume green manures is generally high because they are typically young plants when terminated (Gardner and Faulkner 1991) and contain higher concentrations of protein and minerals than grasses (Hafley et al. 1987; Fraser et al. 2004). The crude protein (CP) concentration of annual legumes such as hairy vetch, chickling vetch, clovers, medics, and peas ranges from about 80 to 290 g kg^{-1} (Hafley et al. 1987; Shrestha et al. 1998; Fraser et al. 2004). In addition, Fraser et al. (2004) reported acid detergent fibre of 180–460 g kg^{-1} and neutral detergent fibre values of 240–500 g kg^{-1} for 15 varieties of legumes including annual medics, vetches, clovers and alfalfa. These authors also indicated that for many of the species studied, forage quality parameters would meet the nutritional requirements of beef cows. The optimal CP concentration for animal production varies by species and physiological stage, and ranges from 70 to 190 g kg^{-1} DM (Buxton and Mertons 1995). Thus, the protein level of some annual green manure legumes may actually be too high for optimal nutrition. Carr et al. (1998) found that increasing the cereal component of a cereal-pea forage intercrop from 93 to 185 seeds m^{-2} reduced forage CP; thus, intercropping annual forage legumes with cereals may bring the CP of the annual green manure into a more desirable range. Legume CP concentration decreases with plant maturity (Hafley et al. 1987), so grazing green manures at a more mature stage of development may also accomplish this goal. Further research is required to match the forage quality parameters of annual green manures to the requirements of various classes of grazing livestock.

Reports on palatability of annual green manures vary. While many sources state that hairy vetch makes good forage (Undersander et al. 1990; Miller and Hoveland 1995; Hannaway and Larson 2004), others state that ''livestock do not relish it'' (SAN 1998, p. 119) or that cattle will need to be trained to eat it (Kansas Rural Center 1998). Cowpea and soybean [*Glycine max* (L.) Merr.] are reported to be highly palatable to grazing lambs (Sheaffer et al. 1992). In an intensive grazing system, livestock are readily trained to eat a variety of forages, including those they did not previously find palatable (Marten 1978; Thiessen Martens, unpublished observation, 2009, 2010).

Annual legume crops also vary in their adaptation to grazing. Many large-seeded annual legumes (grain legumes) do not regrow well after cutting or grazing, while small to medium-seeded legumes such as berseem clover and vetches offer some regrowth potential (Fraser et al. 2004). Even so, close grazing of hairy vetch will remove axillary buds and limit regrowth; thus, it should not be grazed before it is 15 cm tall (Miller and Hoveland 1995; Sheaffer and Evers 2007). Grazing can also affect the productivity of forage plants through soil compaction, herbage fouling and nutrient redistribution (Follett and Wilkinson 1995).

Depending on the design of the grazed green manure system, regrowth after grazing may or may not be desirable. For instance, a farmer wishing to terminate an annual green manure crop without the use of tillage may use the crop's poor grazing tolerance to good advantage. With most annual green manures, an intensive ''once over'' grazing system, resulting in little or no regrowth, may be easiest to manage.

Rapid plant development may present a logistical challenge for grazed green manure systems. From an N fixation perspective, optimal time of annual green manure termination is at mid-bloom, when biomass production has peaked and before seed set has occurred. Large-scale grazing of annual green manures may require the use of staggered seeding dates and/or planting of several green manures with varying dates of maturity in order to graze all green manure crops at an appropriate stage. Growing a forage mixture that includes a legume with regrowth potential may offer some flexibility in harvest date: Ross et al. (2005) reported higher CP with earlier first cutting of an oat (*Avena sativa* L.)–berseem clover intercrop, but no effect on total DM yield due to compensatory growth by berseem clover after the first cut.

Grazing legume green manures may present some animal health concerns. Problems with bloat have been reported for field pea (Cash et al. 2005) and hairy vetch (Collins and Hannaway 2003; Hannaway and Larson 2004). Others indicate that the bloat risk of hairy vetch is low (Sheaffer and Evers 2007). The risk of bloat can be minimized by including grasses in mixtures with forage legumes and through grazing management strategies such as strip grazing and avoiding moving animals onto lush pastures when they are hungry and when dew is present (Collins and Hannaway 2003). Cattle grazing hairy vetch have developed systemic granulomatous disease in some cases (Johnson et al. 1992; Panciera et al. 1992). In spite of this, hairy vetch is often noted to be a good forage crop. Cattle and non-ruminants grazing chickling vetch may be subject to lathyrism, caused by the neurotoxin β-N-oxalyl-l-α, β-diaminopropionic acid (ODAP). However, the chickling vetch cultivar AC Greenfix, a popular prairie green manure species, has lower levels of ODAPthan older accessions and is acceptable for grazing (Rao et al. 2005).

Potential Animal Productivity in a Grazed Green Manure System

Based on reports of biomass production and known animal productivity parameters, it is possible to estimate the potential for animal live weight gain (LWG) in a grazed green manure system. Estimates of forage requirements per unit of LWG for grazing livestock vary by livestock species and physiological stage as well as forage quality. In general, feed conversion efficiencies for forage-fed sheep and beef cattle range from 9:1 to 17:1 [calculated from Sheaffer et al. (1992), Orr et al. (1995), Estermann et al. (2001, 2003) and Speijers et al. (2004)]. With forage DM production of 5000 kg ha^{-1}, a forage utilization of 50% and a feed conversion ratio of 14, animal LWG from a grazed green manure system would exceed 175 kg ha^{-1}. With the same assumptions but a forage DM production of 2500 kg ha^{-1}, animal LWG would near 90 kg ha^{-1}. Similar examples could be generated for other production systems such as dairy operations.

NUTRIENT DYNAMICS IN GRAZED GREEN MANURE SYSTEMS

Since the primary purpose of growing a legume green manure crop is soil fertility enhancement, specifically with N, the impact of grazing livestock on nutrient cycling is of utmost importance. Integrating herbivores into the system can affect nutrient distribution in the grazed area and nutrient turnover rates and can influence potential pathways of nutrient loss, such as leaching and ammonia volatilization, while also removing nutrients as animal products (Russelle 1992; Follett and Wilkinson 1995; Whitehead 1995, 2000). Examination of these factors is necessary in order to assess the economic viability of grazed green manure systems as well as environmental risk factors.

Nutrient Partitioning and Turnover in Grazing Animals

The proportion of nutrients removed from a grazing system in animal products may affect the ability of the green manure crop to supply nutrients to subsequent crops. Grazing green manures may result in only partial benefits to the following crop because of nutrient and organic matter removal (Department of Agriculture and Rural Development, Northern Ireland 2008). Nutrient partitioning in grazing animals depends on animal factors such as species and maturity as well as on plant factors including as various forage quality parameters (Kawas et al. 1990). Actively growing animals retain a greater proportion of nutrients than mature animals (Follett and Wilkinson 1995) and lactating dairy animals remove a greater proportion of nutrients than meat animals (Berry et al. 2002). Retention of N, P and K by livestock are typically 5–25%, 10–36% and $<$10%, respectively (Haynes and Williams 1993; Whitehead 1995, 2000). Follett and Wilkinson (1995) state that grazing animals generally remove from the system 27.2, 6.8 and 1.5 g of N, P and K, respectively, per kg LWG. Thus, if LWG from a 5000 kg ha^{-1} grazed green manure system was 175 kg ha^{-1}, as discussed above, N, P and K removal in animal products would be 4.8, 1.2 and 0.3 kg ha^{-1}, respectively. This represents approximately 4% of the N, 8% of the P and 0.3% of the K contained in the green manure crop [based on nutrient concentrations in Brink et al. (2001), Barker and Collins (2003), Çelen et al. (2005) and Fageria et al. (2005)].

While nutrient retention (i.e., animal productivity) is important from an economic standpoint, nutrient excretion is equally important in grazed green manure systems. Even at high nutrient retention rates, 70–75% of nutrients ingested by grazing animals are excreted and subsequently recycled within the system. A large proportion of these nutrients is returned to the system in highly plant-available forms, unlike plant material in soil-incorporated green manure crops, which must undergo the process of decomposition and mineralization before the nutrients are plant-available. Therefore, in grazed green manures, the rumen effectively speeds up the cycling of these nutrients within the system (Gardner and Faulkner 1991). This may affect the uptake of nutrients by the following crop, potentially increasing yield.

Fifty percent or more of N excreted is in urine (Bellows 2001; Ledgard 2001; Berry et al. 2002), mainly in the form of urea [$(NH_2)_2CO$], which is readily available to plants (Bellows 2001; Ledgard 2001). The proportion of N excreted in urine is directly related to the N concentration in the diet. When dietary N concentration increases from 1.5 to 4.0%, the proportion of N excreted in cattle urine increases from about 45% to about 80% (Whitehead 1995). Urine also contains large amounts of K and S, while feces contains virtually all of the excreted P, more stable forms of N, and most of the micronutrients (Haynes and Williams 1993; Whitehead 2000). Strategies to reduce N excretion include adding a forage grass with a legume green manure or providing a low-protein feed supplement, which would reduce the protein content of the diet (Misselbrook et al. 2005; Luo et al. 2010). Annual forage grasses, such as spring-planted winter rye (*Secale cereale* L.) or triticale (*Triticosecale*), are also more tolerant of defoliation than annual legumes (Schoofs and Entz 2000) and could take up readily available nutrients in animal excreta as they continue to grow after grazing.

When cover crop biomass has a high carbon:nitrogen (C:N) ratio, predigestion of plant material by grazing animals may reduce the problem of N immobilization following incorporation of cover crops. Grazing non-legume cover crops immediately before seeding wheat increased wheat yield by 22% compared with cover crop incorporation 6 wk before seeding, likely due to reduced N immobilization in the grazed system (Canterbury Organic Growers 2006). This contribution of animals to nutrient cycling is particularly important in conditions where soil biological activity is limited, such as drought or low temperature conditions or where soils are extremely degraded. In these situations, the biological activity present in the digestive systems of grazing livestock may be used to compensate for the limited biological activity in the soil and to stimulate increased soil biological activity. For instance, Miles and Brown (2011) observed that manure applications increased soil organic carbon and active carbon in a Missouri soil that was degraded due to long-term removal of crop residues. This is an area that has received very little research and deserves further investigation.

In-field Distribution of Nutrients in Grazing Systems

One of the major roles of grazing animals in forage systems is the horizontal redistribution of nutrients through consumption of forage and deposition of excreta (Follett and Wilkinson 1995; Bellows 2001). As animals graze, forage is gathered from a large area and when excreted, nutrients are concentrated on a very small area. Each deposition of feces and urine may result in localized N application rates of 130 and 500 kg ha^{-1} in dung and urine, respectively, for sheep, and 1040–2011 and 244–1000 kg ha^{-1} in dung and urine, respectively, for cattle (Haynes and Williams 1993; McGechan and Topp 2004). While reports on the effective N application rate in dung and urine patches vary, these rates are consistently very high and are well in excess of plant requirements.

In addition to the high concentration of nutrients in each deposition, grazing animals typically do not disperse excreta evenly over the grazed area, but will tend to concentrate depositions in areas where animals congregate, such as water or mineral stations, along fencelines, in shaded areas or along paths (Follett and Wilkinson 1995; Bellows 2001; Ledgard 2001). Sheep typically congregate more than cattle and thus result in a more unevendistribution of excreta (Hilder 1969; Follett and Wilkinson 1995). Uneven distribution of excreta results in a net transfer of nutrients from one area to another, causing nutrient depletion in some areas and nutrient accumulation in others. For instance, in an Alberta study, nitrate-N and soil test P adjacent to cattle waterers were seven and three times greater, respectively, than at a distance of 10 m away (Miller et al. 2010). Similarly, in a Georgia study, inorganic N concentration in soil immediately adjacent to livestock gathering points in permanent pastures was 2.2 times higher than in soil 10 m away and 2.8 times higher than in soil 30 m away (Franzluebbers et al. 2000). Concentrations of P and K followed a similar pattern in this experiment (Schomberg et al. 2000). Schnyder et al. (2010) observed a similar pattern in a long-term, extensively managed pasture, but determined that nutrient transfer occurred over a period of many years, since the net N and P transfer in a single year of grazing was only a small fraction of the difference between soil nutrient stocks in the nutrient accumulation zone and the nutrient depletion zone.

The problem of uneven distribution of excreta over the grazed area can be mitigated by grazing management. In a Manitoba study, short-duration rotational grazing was credited with preventing major nutrient redistribution in pastures due to relatively even return of excreta to the soil (Chen et al. 2001). Strategies that discourage animals from congregating in certain areas include use of smaller paddocks and locating water, minerals, shade, etc. further apart in the paddock (Bellows 2001). Animals in small paddocks have been observed to spread out evenly across a paddock and visit watering points individually, while animals in large paddocks tend to function more as a herd (Bellows 2001; Gerrish et al. undated). Relocating shade and water sources periodically will also help to distribute excreta more evenly across the paddock (Franzluebbers et al. 2000). Grazing with sheep rather than with cattle will likely reduce nutrient concentrations in individual dung and urine spots since sheep typically urinate and defecate more frequently and in smaller volumes than cattle (Haynes and Williams 1993; Di and Cameron 2002).

Grazing management can also be used to strategically redistribute nutrients to areas where they are needed. Powell et al. (1998), working in semi-arid Niger, investigated the effect of corralling cattle or sheep directly on cropland between crop cycles, in order to transfer nutrients from native rangelands to cropland. Corralling livestock on cropland for only two nights (dung application rate of 6–15 and 3–9 Mg DM ha^{-1}, for cattle and sheep, respectively) resulted in a 50–100% yield increase in a subsequent pearl millet [*Pennisetum glaucum* (L.) R. Br.] crop compared with plots that received an equivalent amount of dung (no urine) collected elsewhere and applied by hand. This effect carried over into 2 subsequent years, with the optimal system being corralling for two nights every second year. The success of this system was attributed to the recycling of livestock urine in the system along with the solid manure, thus increasing N supply, raising pH and increasing P availability. This concept was also tested in a dairy system in Wisconsin, where corralling heifers on cropland for two or four nights resulted in greater yields in subsequent crops than where manure was collected in the barn and field-applied (Powell and Russelle 2009). The role of livestock in relocating nutrients within agricultural systems is extremely underutilized and is an area that deserves further research.

Nutrient Losses in Grazing Systems

Integrating grazing livestock into a green manure system introduces an additional layer of complexity to the system and may affect pathways of potential nutrient loss, particularly N. While there is plenty of published research on N cycling and losses in legume green manures and in pasture systems, little work has been done on the impact of integrating these two systems and the interactions that may occur. For instance, many reports on N flows in grazed systems are in extensively managed permanent grasslands, which may receive very low N inputs and low levels of disturbance (e.g., Woodmansee, 1978; Russelle 1992). Grazed green manure systems, on the other hand, have high N inputs through BNF and are subject to the disturbances associated with annual cropping.

Estimates of N losses in grazing systems range from 15 to 50% of N consumed by livestock (Whitehead 2000; Kumm 2003, Jürgen et al. 2006). Important N loss pathways include nitrate leaching, ammonia volatilization, denitrification and nitrous oxide (N_2O) emissions. The relative importance of each of these pathways depends on complex interactions among many factors, including climate (i.e., evapotranspiration potential, soil moisture, rainfall events, freeze-thaw cycles), soil properties (i.e., soil texture, pH, organic matter content), plant properties (i.e., N content of grazed plants, regrowth after grazing) and animal considerations (i.e., class and age of livestock, grazing management). While it is beyond the scope of this review to quantify potential N losses from grazed green manure systems, it is important to consider how integration of green manure systems and grazing systems could affect these loss pathways and to explore potential mitigation practices.

When leaching of N from livestock excreta occurs, it is usually localized, as a result of the high concentration of N in dung and urine. Nitrate accumulation in livestock congregation areas, as discussed above, may pose a leaching risk, even in the relatively dry climate of the Canadian prairies (Chen et al. 2001; Miller et al. 2010). The potential for nitrate leaching from urine spots depends on various factors, including intensity of grazing, urine N content, groundwater levels, soil texture, plant uptake, and precipitation (Russelle 1992; Hack-ten Broeke et al. 1996; Di and Cameron 2002; Decau et al. 2004). Leaching is typically higher under intensive grazing (Russelle 1992) and is higher in the latter part of the summer and autumn, when plant uptake is lower (Hack-ten Broeke et al. 1996; Di and Cameron 2002; McGechan and Topp 2004). These are important considerations in intensively grazed green manure systems, where plant growth may be terminated by grazing. It is also important to note the depth of leached N in grazed systems. Since grain crops following grazed legume green manures can grow roots to 120 cm [wheat, canola (*Brassica napus* L.), oats (*Avena sativa* L.)] or 160 cm [sunflower (*Helianthus annuus* L.)], some of the temporarily leached N may in fact be captured by a following crop.

Ammonium from urine spots is also susceptible to leaching through soil macropores when soil is wet. In a model based on a Scottish grazing system on a silty clay loam soil, ammonium leaching from a urine spot was estimated to remain near 0 until air-filled pore space dropped below 13 mm; ammonium N loss increased to 30% and $>60\%$ of N applied when air-filled pore space declined to 10 and 2 mm, respectively (McGechan and Topp 2004). However, when considered over an entire grazing season, losses from urine spots by ammonium leaching were 4.8% in the wet winter period and only 1.2% in the dry summer period.

Since green manure crops have a high N content and would generally be grazed in mid-summer, when evaporation potential is high, ammonia volatilization from this system may be in the high end of the expected range. Reported losses of urinary N to volatilization in grazing systems generally range from about 5 to 50% (Woodmansee 1978; Sherlock and Goh 1984; Whitehead and Raistrick 1991, 1992; Whitehead 2000; Peoples et al. 2001; Ledgard 2001; Eckard et al. 2003), which could be as much as 25% of the N ingested by the animal (based on a 90% return of ingested N, 70% of excreted N in the form of urine, and 40% losses of urinary N to volatilization; Peoples et al. 2001). Volatilization is affected strongly by urinary N concentration (Cole et al. 2005) as well as by other factors, such as air temperature, precipitation events, soil texture, soil pH, cation exchange capacity and N fertilizer application (Whitehead and Raistrick 1991, 1992; Whitehead 2000; Eckard et al. 2003). Losses are particularly high when urine is applied to one spot more than once during the season (Sherlock and Goh 1984), emphasizing the need to distribute deposition of excreta evenly across the grazed area to minimize nutrient losses.

Losses of N through denitrification in grazed systems appear to be small compared with losses through leaching and volatilization. Denitrification losses are estimated to range from 1 to 5.5% of N excreted in urine (Luo et al. 1999; Ledgard 2001) and differ little from denitrification losses in other management systems, such as ungrazed forages or slurry application systems (Luo et al. 1999; McGechan and Topp 2004).

Nitrous oxide emissions from livestock systems are reported to be a major source of greenhouse gases in Canada (Rochette et al. 2008; Beauchemin et al. 2010) and around the world (Oenema et al. 1997; Eckard et al. 2003; de Klein et al. 2006). Manure from grazing animals accounts for 17% of agriculture-related N_2O emissions across Canada (Rochette et al. 2008). One of the main factors affecting N_2O emissions is soil moisture, since N_2O production occurs mainly under anaerobic soil conditions. Thomas et al. (2004) reported no effect on N_2O emissions when urine was applied to soil below field capacity and Liebig et al. (2010) observed a positive correlation between N_2O emissions and water-filled pore space in a North Dakota pasture study. Soil compaction by livestock treading may create more anaerobic sites in the soil and increase N_2O emissions. Oenema et al. (1997) estimated that cattle trampling may double N_2O emissions from grazed grasslands, while the effect of sheep trampling would likely be less. In temperate regions, freeze-thaw cycles can also contribute significantly to N_2O emissions due to N mineralization during freezing and subsequent denitrification during and after thawing (Müller et al. 2002). It is unclear whether N_2O emissions in grazed green manures would be affected significantly by freeze-thaw cycles, since grazing is affecting the form of N in the soil but is not adding N to the system.

While N losses from animal excreta may be substantial, losses from ungrazed green manure systems and fertilized crop production systems also occur. For example, Janzen et al. (2003) estimate that N losses in Canadian agroecosystems are almost 50% of N inputs. More specifically, in research summarized by Di and Cameron (2002), nitrate leaching from grazed pastures was similar to that from arable cropping systems. In a Saskatchewan study, 24 and 30% of N applied through a lentil green manure and synthetic fertilizer, respectively, were lost to denitrification and leaching (Bremer and van Kessel 1992). Volatilization of ammonia from incorporated and unincorporated green manure biomass ranged from near 0 to 14%, respectively, of green manure N (Janzen and McGinn 1991; Vaisman et al. 2011), and was reported to be up to 39% of high-N cover crop residue (Larsson et al. 1998). Volatilization from urea fertilizer may be 10–25% (Whitehead 2000). Reports from selected literature indicate that N leached from green manure systems can range from 6 to 48% of N contained in the green manure (Bergström and Kirschmann 2004; Torstensson et al. 2006). In these studies, N leached from legume green manures was similar to that of a non-legume cover crop and a fertilized treatment (Bergström and Kirschmann 2004) and a system receiving animal manure (Torstensson et al. 2006). N_2O emissions from cover crop mulches can be much as 13 kg N ha^{-1} (Larsson et al. 1998). While N losses from pasture-based livestock systems may be high, the losses from confinement systems may be even higher. Powell and Russelle (2009) observed that 20–30% of N excreted by dairy heifers housed in a barn was lost during the manure-handling process, resulting in lower N applications to cropland than when heifers were corralled directly on the land.

Minimizing losses of N from a grazed green manure system is a key factor in both the environmental and economic sustainability of the system. According to Ledgard et al. (2007), strategies to reduce N losses from grazed pastures should focus on losses from animal urine. Green manure crop selection can have an impact. For example, urinary N was reduced from 8.8 to 6.7 g L^{-1} in dairy cattle fed high-tannin forages rather than low-tannin forages (Misselbrook et al. 2005). In the same study, reducing dietary CP from 19 to 14% reduced urinary N from 8.5 to 4.5 g L^{-1} (Misselbrook et al. 2005). In beef cattle, increasing dietary CP from 11.5 to 13% increased in vitro ammonia volatilization by 60 to 200% (Cole et al. 2005). Thus, reducing CP concentration of annual green manures by intercropping with grasses or cereals or by delaying grazing of green manures, as discussed above, may be a key practice in minimizing N losses.

Where nitrate leaching potential is high, the use of N process inhibitors such as dicyandiamide (DCD) may reduce N losses by preventing nitrification. When administered to grazing sheep, DCD reduced nitrification of urinary N by $>90\%$ (Ledgard et al. 2007). When applied to the soil, DCD reduced nitrate leaching by an average of 63% (Di and Cameron 2007). However, use of DCD has also been reported to increase ammonia volatilization by 18–41% due in part to the retention of N in the ammonium form (Zaman and Blennerhassett 2009). These authors reported that including a urease inhibitor [N-(nbutyl)thiophosphoric triamide] together with DCD mitigated this problem and reduced N losses from urine patches through ammonia volatilization, N_2O emissions and nitrate leaching by 48–51%, 55–63% and 42–56%, respectively.

Grazing management also has an important role to play in distribution of excreta and prevention of N accumulation. An intensive once-over grazing system (i.e., strip grazing) may offer the dual benefits of good forage utilization and even distribution of excreta. Avoiding grazing when soils are wet may also reduce N losses through leaching and N_2O emissions (Luo et al. 2010).

Management practices during the transition from green manure to other crops are also crucial. Rotating from grazed systems to cash crops and using shallow tillage to distribute urine and dung patches may reduce the risk of N leaching from grazed green manure systems (Gardner and Faulkner 1991). If a subsequent crop can establish a high demand for nutrients at a time when nutrients are highly available, N losses through leaching will be minimized (Wilkins 2008). In a grazed system, seeding the next crop immediately after grazing cover crops can reduce N losses (Canterbury Organic Growers 2006). In Canada, winter cereals (wheat or rye) could be seeded in late-summer to utilize labile N from grazed green manures. Alternatively, cover crops or catch crops such as oilseed or fodder radish [*Raphanus sativus* (Stokes) Metzger], canola, winter cereals, or even volunteer weed growth could be used to temporarily take up and retain legume N (Baggs et al. 2000; Di and Cameron 2002). These cover crops can potentially provide the additional benefit of late season grazing. Choosing a green manure crop that will tolerate grazing and continue to grow may also perform this function.

Phosphorus Availability in Grazed Green Manure Systems

While much of the emphasis in this review has been placed on N dynamics, P availability is also an area of interest, especially in long-term organic crop production systems, where plant-available P tends to become depleted and is not easily replenished (Entz et al. 2001; Gosling and Shepherd 2005). Livestock manure is a valuable source of P in these organic crop production systems (Welsh et al. 2009), and thus might be expected to increase plant-availability of P in grazed green manure systems. Alberta researchers have observed greater extractable P in pastures under heavy grazing (154 mg kg^{-1}) than in those under light grazing (127 mg kg^{-1}), due to higher levels of excreta deposition (Baron et al. 2001). During digestion by ruminants, a portion of the organic P in the plant material is converted to the inorganic plant-available form (Leech 2009). The proportion of readily plant available (water and bicarbonate extractable) P in fresh cattle and sheep dung has been reported as 72 and 65%, respectively (McDowell and Stewart 2005). McDowell and Stewart (2005) also found that air drying dung resulted in significant movement of P from the labile forms to the more recalcitrant forms. These factors and others may affect the availability of P to the crop following the grazed green manure system. Given the difficulty in supplying P in long-term organic cropping systems, using grazing to increase the plant-availability of P is an area that deserves further research.

OTHER POTENTIAL BENEFITS OF GRAZED GREEN MANURE SYSTEMS

Integrating grazing livestock into green manure systems may bring with it a variety of additional benefits. Research has shown that including grazing or manure applications in cropping systems can result in greater soil microbial biomass, soil organic matter and active carbon (Fließbach et al. 2007; Franzluebbers and Stuedemann 2008; Miles and Brown 2011). According to Jacobson (1999), an often overlooked benefit of integrating livestock into cropping systems is the bacterial inoculation of soil through animal manure and the resulting positive effects on soil-building. This is an area that has not been investigated and deserves further research.

The physical action of grazing can also be used for various purposes. Gardner and Faulkner (1991) suggest that grazing can be used to either increase or decrease water use in cover crops; grazing may alternatively reduce leaf area to limit water use or maximize growth and increase the transpiration rate of winter cereal cover crops. Grazing livestock can also remove excess plant residues to allow for good seed placement or early-season soil warming (Gardner and Faulkner 1991). Terminating annual green manure crops by grazing rather than tillage may reduce the number of tillage operations required, thus saving fossil fuel energy and protecting the soil from wind and water erosion.

Grazing green manures may have effects on weed populations and communities, and can offer an opportunity for weed management. Visual observation in a Manitoba study suggests that sheep will consume a wide variety of weed species, including Canada thistle [*Cirsium arvense* (L.) Scop.; Thiessen Martens, unpublished observation, 2009, 2010]. Popay and Field (1996) describe many examples of how livestock grazing can provide weed control, although only a few of their examples pertain directly to annual cropping systems. In North America, the beneficial services of livestock in annual cropping systems are generally underutilized and deserve greater attention.

ECONOMICS OF GRAZED GREEN MANURE SYSTEMS

Economic viability is a key factor in farmer adoption of production practices. In many cases, short-term economic return is the primary consideration. For this reason, improving the economics of green manuring within the green manure year is the primary focus in this review, although longer-term effects are also considered.

The economic viability of grazed green manure crops can be compared with that of an ungrazed green manure system, typical of organic farms, or to an annual crop rotation without any green manure, typical of conventional farms. A detailed economic analysis of grazed green manure systems is not within the scope of this literature study, but we will review reports of the economics of some integrated crop-livestock systems and examine the major cost and benefit factors of such a system.

Economics of Integrated Crop-Livestock Systems

In recent history, low fertilizer prices and advancing technology have caused farming systems to become increasingly specialized in the name of high economic returns and efficiency of management (Franzluebbers 2007; Wilkins 2008). Interest in BNF by legumes in rotation has waned, except in times of high energy prices (Silver and Hardy 1976). Despite these trends, integrating livestock into cropping systems is seen by some as a way of increasing profitability (Russelle et al. 2007). Gardner and Faulkner (1991) state that integrating grazing livestock may be a necessary aspect of developing successful cover cropping systems that are economically viable. Anderson and Schatz (2003) reported increased net returns ranging from \$2500 to \$22 000, an increase of almost \$9000 in net worth and a much reduced coefficient of variation in income in mixed farms compared to crops-only operations in North Dakota.

Little work has been done on the economics of grazing green manures and cover crops, especially in short-season regions, but the few reports available suggest that grazing green manures and cover crops increased the profitability of these systems. Profitability analyses on various crop rotations in Wyoming indicated that substituting a fall-seeded, spring-grazed green manure for the fallow phase of a winter wheat rotation increased net returns in the fallow or green manure year by about \$15 acre^{-1} (\$37 ha^{-1}) because of meat sales; income variability was also significantly reduced in rotations that included a grazed green manure instead of fallow (Krall 2002; Haag et al. 2003). A preliminary report from Montana indicated that a fall-seeded annual green manure of peas or lentils grazed in spring could increase net returns by \$10 acre^{-1} (\$24.70ha^{-1}; Montana State University News Service 2008). Researchers in warmer climates such as the south-eastern US have observed annual net returns of \$185 to \$200 ha^{-1} from grazing winter cover crops (cited in Franzluebbers 2007) and even up to \$365 ha^{-1} greater net return over variable costs with grazed winter and summer cover crops compared to ungrazed cover crops (Franzluebbers and Stuedemann 2007).

Major Cost and Benefit Factors in Grazed Green Manure Systems

The primary economic benefit of integrating grazing livestock into green manure systems is the animal LWG or milk production that can be attained as a result. The size of this benefit depends on the productivity of the green manure (i.e., forage biomass produced) and the animals as well as the value of animal products produced. In April 2011, prices for feeder cattle (901+ lb) and lambs (50–100 lb) were \$2.20 to \$2.55 kg^{-1} and \$3.70 to \$4.40 kg^{-1}, respectively [calculated from prices in Manitoba Agriculture, Food and Rural Initiatives (MAFRI 2011)]. With these prices and a LWG of 175 kg ha^{-1} in the Black soil zone, as discussed above, gross revenue from grazing green manures could range from \$385 to \$770 ha^{-1}. With a LWG of 90 kg ha^{-1} in the Brown soil zone, gross revenue could range from \$198 to \$396 ha^{-1}.

Obvious costs involved in a grazed green manure system include the costs of establishing the green manure crop as well as grazing infrastructure (fences, water sources, etc.) and the labour required to manage such a system. The operating costs associated with a sweet clover green manure crop are estimated to be \$47.22 acre^{-1} (\$116.68 ha^{-1}) including the cost of seed undersown to wheat in previous year (MAFRI 2009). Other annual green manures may have higher seed costs than sweet clover. These are costs that most organic farmers already incur, whether they graze the green manures or not. However, for farmers who do not typically produce green manures, these are additional costs not normally incurred.

Capital investments required to move from a stockless system to a grazing/mixed farm system are high, and create financial challenges for adopting such a system (Wilkins 2008). Establishing a new rotational grazing system (including materials for fencing and watering systems) can cost \$30–70 acre^{-1} (\$74–173 ha^{-1}; Undersander et al. 2002). According to Anderson and Schatz (2003), adding cattle to a typical 1200 acre (485 ha) North Dakota farm (dry lot system) would increase annual operating capital requirements by \$7200–\$8200, but would also allow farmers to spread depreciation of farm machinery over more than one enterprise.

Integrating livestock into crop systems can increase labour requirements by more than 50% over crops-only systems, but only a third of the additional labour competes directly with crop-related activities (Gardner and Faulkner 1991). In grazing green manures, most of the grazing management would take place in mid-summer, when crop-related labour demands are lower than at seeding or harvest. For a farm that already has livestock, the additional labour and infrastructure required to implement a grazed green manure system would be relatively low. However, it may still require additional costs for fencing and providing water on land that was not previously grazed.

Other costs that must be considered include the potential effect of nutrient removal in animal products on the yield of subsequent crops as well as losses of N from the grazed green manure system, both of which are discussed above. However, according to the limited research on grazed green manure systems, these costs may be small or non-existent, since crops typically yield as well after grazed cover crops or green manures as after ungrazed ones (Franzluebbers and Stuedemann 2007; Mr. Harun Cicek, personal communication, University of Manitoba, Winnipeg, MB, 2011).

Potential long-term benefits, such as soil health, tilth, biodiversity, and organic matter, are not easily quantified and it is difficult to attach an economic value to such benefits; nonetheless, benefits that are important both economically and environmentally do accrue. In addition, the ecological benefits provided by livestock integration may become a source of income under ecological goods and services programs in the future. It is already recognized that livestock provide ecological benefits in the developing world (Mearns 1996) and interest in programs that value the role of livestock in ecosystem health is growing in western Canada (e.g., Western Stock Growers Association 2011). Further exploration and quantification of the ecological benefits of integrated crop-livestock systems is an area that deserves further research.

SUMMARY AND CONCLUSIONS

Green manure crops have the potential to provide excellent mid-summer forage for grazing livestock in the Canadian prairies and the Northern Great Plains. They can support substantial animal productivity while returning most of the green manure N and other nutrients to the cropping system. While there is risk of nutrient losses from animal excreta, management of the grazing system and the transition to the subsequent crop can likely minimize the losses of nutrients to the environment. Being a little tested system, the economics of a grazed annual green manure system in a short-growing season region are not well defined. However, based on economic analyses of similar systems and the level of animal productivity discussed above, this type of system appears to be economically viable.

While the objective of this paper is to examine ways of increasing the adoption potential of green manure crops for BNF, the adoption potential of the proposed solution (integrated crop-livestock systems) must also be examined. According to Wilkins (2008), the high cost of manure management compared with fertilizer prices and the management complexity of mixed farms are major factors contributing to the low rate of adoption of mixed farming. Additional constraints include the prevalent view that single enterprise farms are the norm, ease of management and government support for large-scale grain cropping systems, increased labour and management requirements in integrated systems, "a lack of appreciation and understanding among many producers for system-level performance" and a lack of incentives for diversity and sound environmental practices in agriculture (Sulc and Tracy 2007, p. 341). Encouraging adoption of integrated crop-livestock systems requires that a clear economic advantage of these systems be demonstrated, and that these systems be easy to manage (Wilkins 2008).

Grazed green manure systems have the potential to meet these criteria, especially if farmers already own livestock and are not faced with a major capital investment. Establishing grazing systems on green manures involves some additional resources for fencing and watering systems, but requires no additional manure management and can provide valuable mid-summer forage, along with other benefits. For farmers who do not currently own livestock, custom grazing systems on green manure crops could provide benefits to both stockless farmers and neighbouring livestock producers (i.e., area-wide crop-livestock integration; Russelle et al. 2007). Organic farms in particular are in critical need of systems that optimize nutrient cycling and allow producers to capture the synergies created by integrating crops and livestock.

Developing grazed green manure systems for short growing season areas such as western Canada will require field testing of management approaches and productivity parameters with green manure crops suited to local environmental conditions, as well as detailed economic and ecological analyses of these systems.

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