Review: Redesigning Canadian prairie cropping systems for profitability, sustainability, and resilience

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Thiessen Martens, J. R., Entz, M. H. and Wonneck, M. D. 2015. Review: Redesigning Canadian prairie cropping systems for profitability, sustainability, and resilience. Can. J. Plant Sci. 95: 1049–1072. Redesign of agricultural systems according to ecological principles has been proposed for the development of sustainable systems. We review a wide variety of ecologically based crop production practices, including crop varieties and genetic diversity, crop selection and rotation, cover crops, annual polyculture, perennial forages, perennial grains, agroforestry systems, reducing tillage, use of animal manures and green manures, soil biological fertility, organic production systems, integrated crop-livestock systems, and purposeful design of farm landscapes (farmscaping), and discuss their potential role in enhancing the profitability, environmental sustainability, and resilience of Canadian prairie cropping systems. Farming systems that most closely mimic natural systems through appropriate integration of diverse components, within a context of supportive social and economic structures, appear to offer the greatest potential benefits, while creating a framework in which to place all other farming practices. Our understanding of ecological relationships within agricultural systems is currently lacking, and a major shift in research, education, and policy will be required to purposefully and proactively redesign Canadian prairie agricultural systems for long-term sustainability.

Key words: Ecological agriculture, Canadian prairies, profitability, resilience, farming systems, sustainable agriculture


Mots clés: Agriculture écologique, Prairies canadiennes, rentabilité, résilience, systèmes agricoles, agriculture durable

The long-term sustainability of the Canadian agriculture sector depends on its ability to thrive economically while protecting our natural resource base and building resilience to stresses and shocks. Modern agricultural systems prevalent on the Canadian prairies, while often highly productive, are associated with a number of environmental and social issues that threaten the sustainability of the sector, including rising energy and input costs, greenhouse gas (GHG) emissions, loss of biodiversity, soil and water degradation, corporate concentration, global competition in production of bulk commodities, and a steady reduction in the number of farms (Morrison and Kraft 1994; Rude and Fulton 2001; Hoeppner et al. 2005; Pimentel et al. 2005; Pretty 2008; Eilers et al. 2010; Halberg 2012; Kremen and Miles 2012; Malézieux 2012).

Many of these issues stem from reliance on simplified production systems consisting mainly of annual monocultures. Monoculture production systems compromise biodiversity, utilize resources inefficiently, and are susceptible to pest outbreaks (Morrison and Kraft 1994; Altieri 1999; Phelan 2009). Continuous production of annual crops requires constant disturbance (either

Abbreviations: BNF, biological nitrogen fixation; GHG, greenhouse gas; NGP, Northern Great Plains

mechanical or chemical) to maintain the system in the earliest successional state (Thomas and Kevan 1993; Phelan 2009). Despite being a net nutrient exporter (Morrison and Kraft 1994), nutrient pollution in agricultural systems is a problem owing to altered nutrient cycles and poor fertilizer use efficiency (Janzen et al. 2003; Drinkwater and Snapp 2007). Uncoupling of crop and livestock production has exacerbated the problem (Russelle et al. 2007). Based on these observations, Phelan (2009) noted that modern agricultural systems share the characteristics of dysfunctional or highly stressed ecosystems.

Gliessman (2010) argues that improvements in efficiency of input use and input substitution (e.g., herbicides instead of tillage) are not enough to address the challenges facing modern agriculture. Instead, he argues that farming systems must be redesigned based on a new set of ecological relationships. In other words, agricultural systems require systemic change. This review seeks to highlight and evaluate the cropping practices and systems that might make up these redesigned prairie farming systems. Key focus areas include diversified crop production systems, reduced tillage, nutrient cycling through endogenous input systems, integration of crops and livestock, and the purposeful design of farm landscapes (farmscaping); evaluation criteria relate to profitability, environmental sustainability, and resilience. Sources considered in this review include reports and peer-reviewed publications from the Canadian prairie and Northern Great Plains (NGP) regions, where available, relevant studies from other regions, and a few personal communications where published information is scarce.

**DEFINING AND ASSESSING PROFITABILITY, SUSTAINABILITY AND RESILIENCE IN CROPPING SYSTEMS**

A wide range of approaches has been developed to evaluate the potential value of alternative agricultural practices, including both ecological and social components (e.g., Xu and Mage 2001; Darnhofer et al. 2010b; Cabell and Oelofse 2012). While assessment approaches differ, common themes of profitability, sound environmental practice (sustainability), and resilience (both ecological and social), recur throughout the literature.

For the purposes of this analysis, we have identified a potential set of criteria in each of these theme areas, as outlined below and in Table 1. Despite the difficulty in defining appropriate criteria (Darnhofer et al. 2010b; Cabell and Oelofse 2012; Koohafkan et al. 2012), their use here is both to emphasize the need for accepted criteria and to highlight the potential of alternative systems and practices to be better than the dominant industrial agricultural model.

**Environmental Sustainability**

“Systems high in sustainability can be taken as those that aim to make the best use of environmental goods and services while not damaging these assets” (Pretty 2008).

**Profitability**

Profitability refers to the capacity of an enterprise to generate more revenue through the sale of its products than it costs to produce those products. Profitability can be enhanced by increasing production, obtaining a higher price for products, or by reducing costs. Major operating costs in prairie cropping systems include purchased inputs (fertilizers and pesticides), seed, fuel, and labour; thus, any reduction in these inputs while maintaining yield and quality increases profitability.

Profitable market positions may be secured over the long term by developing protectable advantages, where products, processes, knowledge, relationships, and/or conditions are both profitable and difficult for rivals to imitate (Porter 1996). For example, the combination of favourable local growing conditions for a specific product matched with tacit knowledge of production techniques for those conditions can create a relatively secure and stable market opportunity. Direct marketing of specialized products to niche markets can also create opportunities for protectable advantages.

**Table 1. Sustainability, profitability, and resilience assessment criteria of relevance to Canadian prairie cropping systems**

<table>
<thead>
<tr>
<th>Sustainability criteria</th>
<th>Profitability criteria</th>
<th>Resilience criteria</th>
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<tr>
<td>Soil health</td>
<td>Reduced input costs</td>
<td>Resilience to climate extremes</td>
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<td>Reduced soil erosion</td>
<td>Increased production</td>
<td>Reduced energy use</td>
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<td>Dewatering wet soils</td>
<td>Premium prices</td>
<td>Reduced use of external inputs</td>
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<td>Storing water in dry soils</td>
<td>Protectable advantages</td>
<td>Enterprise diversity</td>
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<td>Water quality protection</td>
<td>Income stability</td>
<td>Agroecological integrity</td>
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<td>Air quality protection</td>
<td>Reduced financial risk</td>
<td>Adaptive capacity / flexibility</td>
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<tr>
<td>Ecological nutrient management</td>
<td>Air quality protection</td>
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<tr>
<td>Natural pollination services</td>
<td>Water management</td>
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<td>Natural pest suppression services</td>
<td>Water and air quality protection</td>
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<td>Natural disease resistance</td>
<td>Reduced greenhouse gas emissions</td>
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<td>Reduced greenhouse gas emissions</td>
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Sustainable agriculture practices are based on biological and ecological processes, principally the interactions between soils, crops, and animals (Pretty 2008; Malézieux 2012). Such systems protect natural capital, minimize nutrient losses and use of non-renewable inputs, include recycling and feedback mechanisms, make optimal use of ecological niches, and include high levels of biodiversity, while continuing to be productive (Pretty 2008; Phelan 2009; Koohafkan et al. 2012). Accordingly, key environmental criteria by which to assess these systems centre around soil health, reduced soil erosion risk, effective soil water management, water and air quality protection, effective nutrient management, natural pollination and pest and disease suppression services, GHG emissions, and carbon (C) sequestration (Table 1).
Along with year-to-year profitability, risk management and income stability over years also become important for the long-term economic success of farms (Table 1).

Resilience
Resilience refers to the ability of a system to undergo change while still retaining control of its structure and function (Cabell and Oelofse 2012). Heterogeneity in space and time, as well as functional and response diversity, are key components of both ecological and social resilience. Resilience also requires a certain tension between adaptability and efficiency (Darnhofer 2010a); redundancies within the system and apparent subfunctional diversity may be associated with lower short-term productivity but also provide greater capacity to recover from shocks (Lin 2011; MacDougall et al. 2013).

Farmers play an important role in developing resilience, not only through their farming practices, but also through their ability to learn and adapt. Darnhofer et al. (2010a) identify three elements that affect adaptive capacity: the ability of the farm manager to learn, the flexibility of a system (both its operation and strategic flexibility), and its diversity.

Important indicators of resilience in agricultural systems include the ability to adapt to climate extremes, minimal dependence on external inputs such as non-renewable energy sources, enterprise diversity, agroecosystem integrity, and the flexibility of the system (Table 1).

CROP MANAGEMENT PRACTICES AND SYSTEMS THAT HOLD POTENTIAL FOR THE CROPPING SYSTEMS OF THE CANADIAN PRAIRIES

Diversified Crop Production Systems
Diversification of cropping systems can be achieved through a wide variety of farming practices that purposefully include agricultural diversity in both time and space (Altieri 1999; Kremen and Miles 2012). These practices have the common goal of adding variability in agroecosystem structure and function in areas such as resource use and resistance to pests. Such planned on-farm diversity attracts additional natural biodiversity, further enhancing the integrity of the agroecosystem (Altieri and Nicholls 2008; Liebman and Schulte 2015).

Crop Varieties and Genetic Diversity

Variety Selection. Crop variety selection is based on adaptation to local soil and climatic conditions, yield, ease of management, disease resistance, and end-use quality parameters (e.g., Manitoba Agriculture, Food and Rural Development 2015). Variety selection may also enhance genetic diversity in cropping systems. For example, an Alberta study showed that rotation between three barley (Hordeum vulgare L.) varieties reduced disease incidence and enhanced barley yield and kernel size compared with growing the same variety every year; however, rotating to a different cereal crop species provided even greater benefits (Turkington et al. 2005).

The suitability of crop varieties for low-input, ecologically based production systems may be impacted by the crop breeding environment (Drinkwater and Snapp 2007). Breeders in both Manitoba and Alberta have found that spring wheat (Triticum aestivum L.) lines selected under organic management outyielded conventionally selected lines when all were grown under organic management, and concluded that targeted crop breeding programmes for organic varieties would be beneficial (Reid et al. 2011; Kirk et al. 2012). Similar effects have been observed in other crops such as lentil (Lens culinaris Medik.; Vlachostergios et al. 2011).

Heritage or historical crop varieties have received significant popular attention. Among the few studies that compare the productivity of heritage versus modern spring wheat cultivars, results are inconsistent (Wang et al. 2002). However, some ecological differences have been observed: rhizosphere communities differ between modern and heritage varieties of wheat (Germida and Siciliano 2001) and mycorrhizal colonization has been observed to be greater in older varieties than modern varieties, which may have implications for nutrient acquisition in conditions of lower fertility (Hetrick et al. 1992).

Cultivar Mixtures. Growing mixtures of more than one crop cultivar may be an option for increasing genetic diversity without a large increase in crop management complexity. Intraspecific genetic diversity may play a larger role in ecological interactions than expected: Cook-Patton et al. (2010) found that increasing diversity through variety mixtures resulted in the same level of increase in primary plant productivity as through species mixtures but a smaller increase in arthropod diversity.

According to meta-analysis on wheat and barley cultivar mixtures, crop yields in mixtures tend to be greater than in monocultures (Kiær et al. 2009). Even where yield is not increased, cultivar mixtures may contribute to yield stability (Mengistu et al. 2010) and enhanced yield in otherwise lower-yielding cultivars (Pridham et al. 2007).

The maintenance of grain yield and quality in cultivar mixtures is primarily a result of the disease suppression elicited by genetically diverse cultivars in the mixtures (Mundt 2002). Cultivar mixtures have been used successfully to reduce yield losses from leaf disease in spring barley crops in Europe as well as in spring wheat crops in the United States and Germany (Manthey and Fehrmann 1993; Newton 1997); others have found no benefit to blending cultivars (Dai et al. 2012). A meta-analysis of studies on the effect of spring wheat cultivar mixtures on stripe rust indicated that cultivar mixtures had lower disease incidence in 83% of cases, with an average disease incidence reduction of 28% (Huang et al. 2012).
Mixing resistant and susceptible cultivars may also be used as a strategy to slow or avoid the breakdown of disease (Bing et al. 2011) or insect (Beres et al. 2009; Fox et al. 2010) resistance in crops. However, growing a multi-line oat (Avena sativa L.) variety has been observed to select for complex pathogen races that overcome resistance in all lines (Carson 2009).

Additional processes that may contribute to higher yield of mixtures over monoculture include competition and compensation between the cultivars in the mixture (Finckh and Mundt 1992) or complementary use of resources and divergent niches (Gallandt et al. 2001). Greater diversity in the weed suppression capability of cultivar mixture components appears to contribute to higher yields (Kier et al. 2009). Wheat cultivars may also vary in other traits, such as mineral concentration, leading some researchers to suggest that specific cultivar mixtures could be designed to attain specific nutritional profiles along with high yield (Murphy et al. 2011).

**Crop Selection and Crop Rotation**

Crop selection and crop rotation have potential to enhance sustainability, profitability, and resilience within cropping systems. Choosing crops that are locally adapted and/or adapted to a wide range of conditions provides a level of resilience to extreme weather conditions. For example, many crops grown in the Canadian prairies have flowering dates and life cycles that allow them to tolerate cool temperatures and moisture-deficit stress (Bueckert and Clarke 2013). Further, characteristics such as associated microbial communities, plant and root architecture, and composition of residues and root exudates vary widely between plant species, providing functional diversity that supports ecosystem processes such as nutrient cycling and soil building (Drinkwater and Snapp 2007).

Annual cropping systems can be diversified by extending crop selection over temporal and spatial scales. Crop rotation is widely recognized as a useful tool for weed, disease, and insect management, as well as soil health and nutrient management, and the positive effects of varying crop sequences on crop yields are well documented (e.g., Arshad et al. 2002; Campbell et al. 2011; Davis et al. 2012). Strategic inclusion of diverse species that encompass a wide range of functional groups helps to create cropping systems that effectively support key ecological processes (Altieri 1999; Entz et al. 2002; Drinkwater and Snapp 2007; Lin 2011).

Diversified crop rotations have been observed to increase overall yield, provide more stable profits over time, and reduce input requirements (Smith et al. 2008; Davis et al. 2012). They also have reduced potential for nitrate leaching (Malhi et al. 2009) and tend to be more efficient in their energy use and produce lower levels of GHG emissions (Zentner et al. 2011b). Including legumes in rotation may have a relatively large impact on GHG emissions and energy use due to biological nitrogen (N) fixation (BNF) and the accompanying reduction in N fertilizer requirements (Asgedom and Kebreab 2011).

**Cover Crops**

Cover crops are any crop grown for the purpose of protecting and/or improving the soil, rather than for harvest of a product. More specific goals of cover crops may include BNF, weed or pest suppression, prevention of soil erosion, or others. As such, cover crops have considerable potential to increase the functional diversity and environmental sustainability of cropping systems (Drinkwater and Snapp 2007). Choosing a cover crop species and a method for including it in the cropping system requires careful examination of the spatial and temporal niches available in a cropping system (Thiessen-Martens and Entz 2001; Snapp et al. 2005).

**Interseeding and Relay Crop Systems for Cover Crops.** Growing an understory crop or cover crop together or staggered with a cash crop may fill a spatial or temporal niche in an annual cropping system. Interseeding or relay cropping is a common approach to successfully establishing and gaining the benefits of a cover crop in regions with shorter growing seasons, and has received a certain amount of attention in the NGP (e.g. Bruulsema and Christie 1987; Thiessen-Martens et al. 2001; Blaser et al. 2011).

Crop productivity and cover crop benefits in interseeded systems depend on resource use dynamics in the cover cropping system as well as any effects on the following crop. In cover crop systems using spring-seeded mixtures of cash crops and annual or perennial forage legumes [berseem clover (Trifolium alexandrinum L.), annual medics (Medicago spp.), red clover (Trifolium pratense L.) or hairy vetch (Vicia villosa Roth)], interseeded legumes added N to the system, had variable effects on weed biomass, and increased the yield of the following crop in some cases (Moynihan et al. 1996; Sheaffer et al. 2001, 2002; Pridham and Entz 2008). Effects on the yield of the interseeded cash crop were variable, depending in part on seeding rates, soil texture, and moisture conditions. Achieving the optimum balance of cash and cover crops in interseeded cover crop systems will require testing of promising combinations under various conditions.

Relay cropping systems may allow for more control over resource competition between the cash crop and the cover crop and better use of moisture and heat resources throughout the growing season. Many locations across the southern prairies receive enough growing degree days after winter wheat harvest to produce a cover crop; however, southern Manitoba may be the only region that consistently receives enough late-season moisture (Thiessen-Martens and Entz 2001). In regions receiving inconsistent late-season precipitation, late-season cover crops could be used opportunistically.
In Manitoba, red clover and alfalfa (*Medicago sativa* L.) were successfully established as spring-seeded relay crops in fall-seeded winter cereals (Thiessen Martens et al. 2001; Martens et al. 2005; Cicek et al. 2014a). In Alberta, red clover, alfalfa, and winter pea (*Pisum sativum* L.) were established successfully with winter cereals in both fall and spring plantings (Blackshaw et al. 2010). In all these studies, biomass production by cover crops varied widely, ranging from near 0 to over 4000 kg ha\(^{-1}\). Yield benefits to the subsequent crop were observed in all studies in treatments where legumes established and grew successfully. Blackshaw et al. (2010) also observed weed suppression by the alfalfa cover crop.

Late-season cover crops can have an impact on soil moisture and microclimate. Studies in Manitoba and Alberta have reported reduced soil moisture following productive cover crops (Thiessen Martens et al. 2001; Kahimba et al. 2008; Blackshaw et al. 2010). Soil water depletion by the cover crop can be a detriment in dry climates and a benefit in wet climates. Moderation of near-surface air and soil temperature has also been observed in cover crop systems, with implications for depth of frost, snowmelt infiltration, and potentially nutrient cycling and pest cycles (Thiessen Martens et al. 2001; Kahimba et al. 2008).

Harvesting the main crop as forage rather than grain allows for adaptation of the legume interseeding system to shorter growing season areas. Berseem clover intercropped with various cereals in northern Alberta produced an average of 12.5 Mg ha\(^{-1}\) of total growing season biomass, with 2.1 to 3.4 Mg ha\(^{-1}\) obtained from regrowth of berseem clover after cereal forage harvest (Ross et al. 2004).

**Double Cropping Systems for Cover Crops.** Double cropping, which involves producing a second crop after the harvest of the first crop, offers another opportunity to utilize the late-season heat and moisture resources after cash crop harvest. Early-harvested crops, such as winter cereals or annual forages, can provide a window of opportunity for double cropping with cover crops in the Canadian prairies (Thiessen Martens and Entz 2001).

Establishment of the second crop after main crop harvest can be challenging due to extremely variable precipitation during this period (Thiessen Martens and Entz 2001). Researchers in southern Manitoba have successfully established double crops after winter cereals over several years of research. However, biomass production of these crops has been extremely variable, ranging from 95 to 2357 kg ha\(^{-1}\) for double-cropped black lentil, hairy vetch, and field pea; biomass production exceeded 1000 kg ha\(^{-1}\) in only a few instances (Thiessen Martens et al. 2001; Cicek et al. 2014a).

**Self-regenerating Cover Crops.** A deterrent to implementing cover cropping systems is the cost and uncertainty of establishing cover crops. Self-regenerating cover crops, which reseed themselves, have the potential to address this issue. Adaptations of the ley farming system of Australia, where self-regenerating subterranean clover (*Trifolium subterraneum* L.) and annual medic are grown in pasture-grain systems (Grace et al. 1995), are being explored in both fallow-based and continuous grain production systems, with and without livestock, in the NGP (Carr et al. 2005a, b; May et al. 2010).

Annual medics, especially black medic (*Medicago lupulina* L.), and birdsfoot trefoil (*Lotus corniculatus* L.), can regenerate successfully from the seedbank in the NGP and have potential as self-regenerating cover crops in this region (Sims et al. 1985; Sims and Slinkard 1991; Braul 2004; Carr et al. 2005a, b; May et al. 2010). In North Dakota, annual medic species established in a continuous grain production system in 1991 were still regenerating 8 yr later and provided significant forage for late-season grazing and weed suppression while producing enough seed to successfully re-establish themselves each year (K. Aldridge, NDSU extension agent, Sheridan county, ND, personal communication).

Biomass production of self-regenerating cover crops in annual cropping systems studies varied widely, ranging from near 0 to over 3000 kg ha\(^{-1}\) in North Dakota and Saskatchewan (Carr et al. 2005b; May et al. 2010). Available soil moisture appeared to be the main factor affecting biomass production in both studies.

Effects of self-regenerating legumes on crop yield vary. In long-term field trials in Montana, wheat yield was 1300 kg ha\(^{-1}\) greater in a system with ‘George’ black medic grown during the fallow phase of rotation than in a standard fallow-based rotation (Sims et al. 1985). Carr et al. (2005b), in North Dakota, reported yield reductions in systems with self-seeding forage legumes in some cases, due to soil water depletion, while in other cases there was no effect on yield. At Indian Head, SK, May et al. (2010) found that after several years of including black medic in annual crop rotations, crop yields were increased by up to 57%, but only where fertilizer was applied at 20% of the recommended rate, suggesting that medics may provide the greatest benefit in organic and low-input crop production systems.

Forage quality characteristics of black medic are equal or superior to those of alfalfa and red clover (Carr et al. 2005a). Grazing ruminant livestock may promote increased legume reseeding by removing crop residue while simultaneously burying legume seeds through hoof action (Carr et al. 2005b).

Screening of self-regenerating legumes for local adaptation in central Manitoba (Entz et al. 2007), Wyoming (Walsh et al. 2001), and Minnesota (De Haan et al. 2002) has failed to identify a particular species or genotype that would satisfy all the requirements of a self-regenerating cover crop system, but has indicated that desirable characteristics were present in the screened germplasm and that these qualities could be further developed.
Cover Crops for Weed Suppression. Cover crops grown specifically for weed suppression are often referred to as smother crops or living or killed mulches. These cover crops function by creating a physical barrier to weed growth and/or through allelopathic effects. Fall rye (Secale cereale L.) is known to have allelopathic effects on certain weed species but not on large-seeded crop seeds such as edible beans (Phaseolus vulgaris L.; Flood and Entz 2009). In Alberta, a short-duration fall rye cover crop during the fallow phase of rotation suppressed weeds and offered soil protection, while maintaining subsequent crop yields (Moyer et al. 2000). Killed mulch systems for field scale cropping using a crimper-roller are under investigation in various locations in North America (e.g., Davis 2010; Mischler et al. 2010; Vaisman et al. 2011).

Green Manures/Annual Forages. In regions where heat and/or moisture resources are limiting, the benefits of cover crops may be realized by producing annual forages or green manure crops during the main growing season. Along with the benefits typically associated with cover crops, producing annual green manures or forages offers an opportunity to apply a level of management diversity that is not typically available in annual cash cropping systems. For instance, crop choice and seeding date can be adjusted to allow for strategic weed control operations (mechanical or chemical) before and/or after cover crop growth. Early harvest or incorporation of biomass can prevent weed seed return.

Annual forage legumes can typically produce 2 to 6 Mg ha\(^{-1}\) of biomass under rainfed conditions on the Canadian prairies, with some reports of over 10 Mg ha\(^{-1}\) (Bullied et al. 2002; McCartney and Fraser 2010; Entz et al., unpublished data). Both cool- and warm-season annual cereals grown for forage can produce typical yields of 3 to 8 Mg ha\(^{-1}\) and can provide mid- to late-season grazing, either as a standing crop or in swath (May et al. 2007; McCartney et al. 2008, 2009; Lenssen et al. 2010). Mixtures of annual cereals and legumes can produce large amounts of high-quality forage biomass (Carr et al. 1995, 2004; Strydhorst et al. 2008).

McCartney and Fraser (2010) have described in detail the potential role of annual forage legumes in Canada and conclude that, despite growing recognition of their benefits, it remains challenging to find a niche for these crops due to economic barriers. Grazing green manures and annual forages, rather than soil-incorporating them or harvesting them as green feed or silage, may offer some economic benefits as well as the ecological benefits of integrating livestock directly into annual cropping systems (Thiessen Martens and Entz 2011), though only limited research has been conducted in this region (McCartney et al. 2009; McCartney and Fraser 2010).

Annual Polyculture
Grain intercropping or annual polyculture, in which more than one crop is harvested for seed, offers another option for increasing diversity within annual cropping systems. There is limited documented research work on grain intercropping in the NGP and the results of this research are inconsistent. Overyielding and greater yield stability have been observed in some crop combinations and under some conditions, but not in others (Carr et al. 1995, 2004; Szumigalski and van Acker 2005; Kaut et al. 2008; Pridham and Entz 2008; Hummel et al. 2009; Nelson et al. 2012).

In spite of a lack of clear evidence for increased yield, many studies report other benefits such as weed suppression (Carr et al. 1995; Szumigalski and van Acker 2005; Pridham and Entz 2008; Nelson et al. 2012), lower levels of plant disease (Vilich-Meller 1992; Jensen et al. 2005; Pridham and Entz 2008; Hummel et al. 2009), enhanced nutrient cycling (Szumigalski and van Acker 2006), and enhanced seed quality (Hummel et al. 2009). Positive effects of intercropping on insect populations have not been observed in research from the prairie region (Weiss et al. 1994; Butts et al. 2003; Hummel et al. 2009).

The benefits of intercropping may also be realized in non-grain crops such as cover crops, green manures, and annual forages. These types of polycultures may offer a more accessible opportunity to take advantage of the benefits of intercropping, as harvest processes are no more complex than for monocrops. Cover crop mixtures have been observed to be more productive than individual cover crop species grown alone (Wortman et al. 2012). Annual forages that are grazed or harvested as hay or silage can be grown as mixtures very successfully, while improving forage quality and productivity (Carr et al. 1998).

Perennial Crops in Rotation
Perennial crops are important in developing sustainable and resilient cropping systems because of their constant soil cover, efficient resource use, promotion of beneficial organisms, benefits to water quality and quantity, C sequestration, and reduced GHG emissions (Pretty 2008; Asgedom and Kebrab 2011; Asbjornsen et al. 2014). While forages are the most common perennial crop in the Canadian prairies, perennial grain crops are also being developed.

Perennial Forages. Perennial crops are rotated with annual crops on 5–15% of arable land in the NGP region (Entz et al. 2002). The benefits of perennial forages in rotation are well documented (Entz et al. 2002; Olmstead and Brummer 2008). A key benefit of perennial forages in rotation is yield of annual rotation crops. In a long-term study in northern Alberta, wheat yields after forage were 66–114% percent greater than continuous wheat for 8 yr after forage termination (Hoyt 1990). Farmers have also observed yield increases due to forages in rotation, with 71% reporting enhanced grain yields after forages.
Perennial forages, especially legumes, can have a major impact on soil nutrient status. N contributions by an alfalfa hay crop in southern Manitoba were 84, 148, and 137 kg N ha\(^{-1}\) in the first, second, and third years of the stand, respectively (Kelner et al. 1997). Even short-duration stands (1–2 yr) can provide significant yield increases in subsequent crops (Kelner and Vessey 1995; Bullied et al. 2002). However, forage legumes also remove large quantities of nutrients from the soil, especially in hay systems. Phosphorus depletion can occur within a relatively short time frame, especially under organic management, where nutrients are not replaced; however, returning livestock manure to the system can close the nutrient cycle and prevent depletion of soil nutrients (Welsh et al. 2009). Harvesting forage by grazing instead of haying would automatically cycle most of the nutrients within the system (Sigua et al. 2006), without the cost of removing hay and applying manure.

The effects of perennial forages on other rotation crops also include non-nutrient factors. Perennial forages contribute to enhanced soil health and pest suppression, both of which can provide benefits to subsequent crops (Entz et al. 2002 and references therein; Olmstead and Brummer 2008; Meiss et al. 2010). Moisture availability is a major determinant of forage-related benefits, since moisture depletion by perennial forages can reduce yield of subsequent crops in dry regions (Entz et al. 2002); however, no-till establishment and termination of perennial forage stands can allow their successful integration in more arid regions of the prairies (Jefferson et al. 2007). Water use by forages can be beneficial for dewatering soils in regions with excess moisture and for salinity management (Entz et al. 2002).

The environmental benefits of perennial forages are well documented. Their deep root systems are able to retrieve nutrients from subsoil, thus reducing nitrate leaching, and can sequester C deep in the profile (Entz et al. 2002; Olmstead and Brummer 2008; Malhi et al. 2009). Perennial forages also provide habitat for wildlife, in particular nesting birds and pollinators (Jefferson et al. 1999; Carvell et al. 2006; Arnold et al. 2007).

Economic benefits of including perennial forages in rotation include lower input costs and reduced income variability, along with enhanced crop yields as discussed above (Entz et al. 2002). The length of the forage stand is key to determining its economic value; some have noted that a 4–5 yr stand is optimal (Jeffrey et al. 1993).

**Perennial Grains.** A novel approach to growing harvestable grains in an ecologically sustainable manner is perennial grain crops. Perennial grains have the potential to be high yielding and economically viable, since they use resources more efficiently and may be grown on land that is less suited to annual cropping (Glover et al. 2010). They also have considerable potential to address many of the environmental concerns associated with annual agriculture by reducing tillage, offering continual soil cover, enhancing soil health, increasing nutrient and water use efficiency, reducing GHG emissions, and providing wildlife habitat (Pimentel et al. 2012).

Researchers at the Land Institute in Kansas have been working at developing perennial grain crops for many years and others around the world have joined the effort (Glover et al. 2010; Pimentel et al. 2012; Batello et al. 2014). So far, the main crop of focus has been wheat, with efforts also being devoted to sorghum (Sorghum spp.), sunflower (Helianthus spp.), rice (Oryza spp.), rye, maize, and others (Pimentel et al. 2012). Recent evaluations of perennial cereal lines in Australia and the United States indicate that progress has been made in developing cereals with both a perennial habit and adequate seed production (Hayes et al. 2012; Jaikumar et al. 2012). These authors also noted a high degree of variability in seed quality characteristics such as size and hardness, morphological characteristics such as tiller number and height, and grain yield, indicating considerable potential to select for specific desirable traits.

Lower yields in perennial grains developed so far tend to be due to lower harvest index (i.e., proportion of grain to total biomass) and lower kernel weights than in annual grain crops (Jaikumar et al. 2012). Continued breeding efforts are expected to narrow these gaps. Lower yields may also be offset economically by reduced input costs, as fertilizer and pesticide requirements are expected to be lower due to better resource use efficiency and pest resistance (Pimentel et al. 2012). Perennial wheat may only need to yield 65% of annual wheat to make it economically feasible, or only 40% of annual wheat if perennial wheat could produce both forage for livestock and grain (Bell et al. 2008).

Perennial grain research in Manitoba and Alberta currently focuses on intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkworth & D.R. Dewey], sunflower (*Helianthus maximilliani* Schrad), and perennial cereal rye (Doug Cattani, University of Manitoba, personal communication; Jamie Larsen, Agriculture and Agri-Food Canada, Lethbridge, personal communication). Agronomic trials investigating nutrient management and post-harvest renovation of intermediate wheatgrass began in Manitoba in 2013.

Various approaches have been presented for management of perennial grain crops, ranging from a permanent perennial polyculture of grasses, legumes, and composites, mimicking a native prairie ecosystem (Piper 1998), to simpler systems in which perennial grains are included as a phase in rotation with annual crops or in companion or relay cropping systems (Bell et al. 2010).

**Perennial Polycultures.** The benefits of polyculture observed in annual crops are also attainable in perennial crops. Perennial forages are commonly grown in...
polyculture to provide a balanced nutritional profile and create yield stability under varying weather conditions. In US studies comparing productivity of perennial prairie mixtures to monocultures of these plants, overyielding by mixtures was greatest and most consistent in more diverse mixtures (four or more species) and increased over the years of the study (Picasso et al. 2011; Bonin and Tracy 2012). Similarly, mixtures of grasses and legumes grown at several northern Europe sites outperformed monocultures of these species in terms of productivity and resistance to weed competition (Sturuldottir et al. 2013). Overyielding in these studies was attributed to N fixation by legumes, niche complementarity, and resource use efficiency in mixtures. Sanderson et al. (2007) also suggest that diversity in perennial forage stands provides yield stability where stresses such as drought occur and where there is variability in soils, landscape, and climate. As such, perennial polyculture adds a degree of resilience to agricultural systems.

**Woody Plants in Cropping Systems (Agroforestry)**

Agroforestry systems deliberately integrate woody plants (trees, shrubs) into agricultural production systems (Lassoie and Buck 2000). Established approaches to incorporating permanent woody vegetation into grain cropping systems include field shelterbelts, multipurpose buffer strips, and alley cropping (tree-based intercropping) systems. Agroforestry systems vary widely in their purpose for establishment and in the physical arrangement of crop and tree areas, but all have the potential to contribute to the environmental sustainability and resilience of prairie cropping systems and, in some cases, provide harvestable products that enhance system profitability.

Adding woody plants to cropping systems through agroforestry adds biological and functional diversity to the system, both through planned and associated biodiversity (Altieri and Nicholls 2008). Ecosystem services derived from agroforestry practices typically include pollination services from wild pollinators; suppression of crop pests and diseases; nutrient cycling; C sequestration; water purification, cycling and retention (including salinity management); soil conservation; and regulation of soil organic matter (Altieri and Nicholls 2008; Lin 2011).

**Shelterbelts and Ecobuffers.** Shelterbelts or windbreaks were established widely across the Canadian prairies as a result of the Prairie Shelterbelt Program administered by Agriculture and Agri-Food Canada since 1901. The primary purpose of these tree plantings was for soil conservation and snow capture, both of which are related to reducing wind speed. Shelterbelts with optimal porosity (30%) can reduce wind speed by as much as 71%, and a 20% reduction in wind speed may occur over an area 25 times the height of the shelterbelt (Heisler and Dewalle 1988; Loeffler et al. 1992).

Significant reductions in soil loss from fields sheltered by trees have been observed in the Canadian prairies, along with modest increases in crop yield under certain weather conditions (de Jong and Kowalchuk 1995). While protection of soil from erosion offers a direct benefit to the producer, maintenance of soil health also produces a large public, or external, benefit. The public benefit derived from reduced soil erosion as a result of the distribution of tree seedlings across the Canadian prairies over a 20-yr period has been estimated at $15–97 million (Kulshreshtha and Kort 2009). Soil moisture may also be increased in the vicinity of shelterbelts due to snow capture and reduction of moisture loss from snow through sublimation (Kort et al. 2012). Shelterbelts that are well designed, with consideration of features such as spacing and porosity, can optimize snow capture and distribution across the field (Canada–Alberta Environmentally Sustainable Agriculture 1994; Scholten 1988; Kort et al. 2012). Reduction of wind speed during summer months may also reduce evaporative losses and microclimate effects (increased temperature and humidity) may increase crop water use efficiency (Davis and Norman 1988).

Shelterbelts have been associated with other benefits, such as increased soil organic C, reduced soil bulk density, improved air and water quality, enhanced biodiversity (along with associated recreational activities such as birdwatching), reduced pesticide drift, and improved aesthetics (de Jong and Kowalchuk 1995; Kulshreshtha and Kort 2009).

Multifunctional shelterbelts (termed “ecobuffers”) that directly enhance ecological services such as wildlife habitat, pollination, nutrient cycling, pest suppression, C sequestration, and/or production of food, fuel, or timber are currently being developed and investigated in western Canada (Schroeder et al. 2011).

**Alley Cropping or Tree-based Intercropping.** Alley cropping systems (also called tree-based intercropping systems) include trees planted in widely spaced rows with agricultural crops grown in the alleys between the rows. These trees may be established for varying purposes, including fruit or nut production, timber production, or bio-energy production. Alley-cropping research in Canada has typically focused on bio-energy and timber species of trees, mainly hybrid poplar (Populus spp.); however, potential exists to include other types of trees, such as saskatoon berries (Amelanchier alnifolia Nutt.), sea buckthorn (Hippophae rhamnoides L.), and hardy sour cherries (Prunus cerasus L.) in agroforestry systems on the prairies.

The environmental and ecological services of trees in alley-cropping systems are well documented and have been the focus of several studies in eastern Canada. Benefits include increased soil organic C and greater C sequestration (Thevathasan and Gordon 2004; Peichl et al. 2006; Oelbermann and Voroney 2011); reduced
leaching of water contaminants including nitrate and E. coli (Thevathasan and Gordon 2004; Dougherty et al. 2009; Bergeron et al. 2011); reduced N$_2$O emissions (Beaudette et al. 2010); enhancement, diversification and stabilization of arbuscular mycorrhizal fungus populations (Chifflot et al. 2009; Lacombe et al. 2009; Bainard et al. 2012); and augmentation of earthworm, bird and insect populations (Thevathasan and Gordon 2004). Some of these effects have been observed in relatively young agroforestry systems, only 5 to 8 yr old. Elsewhere in North America, researchers have observed other beneficial effects including retrieval of nutrients from deep in the soil profile (Zamora et al. 2009), a shift in arthropod communities toward parasitic and predatory insects rather than herbivorous arthropods (Stamps et al. 2002), and increased mortality of alfalfa weevil, an important pest of alfalfa (Stamps et al. 2009).

Alley-cropping systems can increase total productivity. A European study found that land equivalency ratios for these systems were consistently greater than 1; however, high productivity levels depend on high soil moisture availability and system designs that optimized complementary resource use (Graves et al. 2007). In Canada, crop yields in alley-cropping systems were lower for C$_4$ crops such as corn (Zea mays L.), similar for cool-season crops such as wheat and canola (Brassica napus L.), and variable for soybean [Glycine max (L.) Merrill], a warm-season C$_3$ plant (Thevathasan and Gordon 2004; Reynolds et al. 2007; Dougherty et al. 2009; Rivest et al. 2009; Beaudette et al. 2010). Yield reductions in these systems have been attributed to competition for light (Thevathasan and Gordon 2004; Reynolds et al. 2007; Rivest et al. 2009). Conversely, workers in the US Midwest have found competition for water to be the main factor in crop yield reduction (Jose et al. 2000). In Europe, crop yield in agroforestry systems was observed to decline over time, due to increased competition from trees as they mature (Graves et al. 2007). These studies highlight the importance of developing tree-based intercropping systems that are locally adapted, allow component crops to interact in a complementary rather than competitive manner, and plan for stand succession.

Economic analysis of agroforestry systems is complex and US studies often compare agroforestry systems to sole forestry operations (e.g., Benjamin et al. 2000; Stamps et al. 2009). Canadian tree-based intercropping systems have been found to be less profitable than annual cropping systems, due to reduced area for annual crops and low revenue from trees, especially when trees were slow-growing timber species (Toor et al. 2012). Conversely, a European study found that many agroforestry systems were economically attractive, especially if high-value tree species were chosen (Graves et al. 2007).

Reducing Tillage
In North America, particularly in dry regions, conservation tillage and no-tillage are widely practiced for soil moisture conservation, soil protection from wind and water erosion, and to reduce fuel use in farm operations (Derpsch et al. 2010). Positive effects of no-till on soil health parameters have been widely documented and include major reductions in soil erosion and fuel consumption, reduced CO$_2$ emissions, and enhanced water quality, biological activity, soil fertility and production stability (Pretty 2008; Derpsch et al. 2010; Lafond et al. 2011 and references therein). Studies in the NGP have also reported better soil aggregation, enhanced soil organic C, and increased potentially mineralizable N in no-till soils (McConkey et al. 2003; Liebig et al. 2004; Pikul et al. 2009; Malhi et al. 2009; Lafond et al. 2011). Microbial biomass, especially of mycorrhizal fungi, is often, but not always, greater in no-till soils (Liebig et al. 2004; Helgason et al. 2010; Monreal et al. 2011); soil organism community structure may also be different in no-till than tilled soils (Helgason et al. 2010).

Yields of crops under no-till vary, depending on crop species and weather conditions (e.g., Malhi and Lemke 2007). No-till often increases crop yields and water use efficiency under dry conditions, but can result in reduced yield under wet conditions (Azooz and Arshad 1998; Arshad et al. 2002). Reduced N mineralization under no-till may also reduce yields where N is limiting (Campbell et al. 2011). Lafond et al. (2011) observed that N uptake and yields in long-term (31 yr) no-till exceeded those in short-term (9 yr) no-till, suggesting that even after 9 yr, and possibly even after 31 yr, no-till soils may still be in a soil-building phase. No-till systems may offer an additional contribution to sustainable cropping systems by facilitating the cycling of perennial forages in rotation (Allen and Entz 1994).

Conservation agriculture is defined by a broader set of principles that include diversity of crop rotations along with minimal soil disturbance and retention of crop residue on the soil surface (Scopel et al. 2013). Conservation agriculture is being implemented widely in tropical countries, particularly those using non-mechanized farming practices, with major improvements in crop yields and soil health (Derpsch et al. 2010). Strengthening crop diversity through improved rotations and cover crops in Canadian prairie no-till systems could have major benefits for their productivity, sustainability, and resilience. The Brazilian model of conservation agriculture, in which cover crops and grazing livestock are central to the system (e.g., Carvalho et al. 2010; Santos et al. 2011), could inform our Canadian prairie systems. For instance, inclusion of N-rich legume cover crops and grazing livestock could enhance N mineralization and provide weed management options that would allow our no-till systems to reduce their current reliance on herbicides.

Endogenous Input Systems
Natural ecosystems function on the principle of microbe-mediated nutrient recycling within the system, with limited external inputs. In contrast, most modern cropping systems have become heavily dependent on
synthetic fertilizer application for delivery of nutrients to crops (Drinkwater and Snapp 2007). The high energetic (Hoeppner et al. 2006; Bavec et al. 2012) and financial cost of fertilizer, nutrient losses to the environment, and the effects of synthetic fertilizer use on soil organic matter and soil microbial communities (Janzen et al. 2003; Drinkwater and Snapp 2007; Phelan 2009) have led many to consider ways of reducing fertilizer use and instead provide crops with at least a portion of required nutrients from within the system (endogenous inputs). Phelan (2009) asserts that “[u]nderstanding the operation of detrital food webs and designing agricultural nutrient management that is more consistent with the nutrient cycles of natural systems is the single most important step that can be taken to increase the economic sustainability, environmental compatibility and biological resilience of agricultural systems.” Because agricultural systems necessarily export some nutrients, entirely closed-loop systems will be impossible to achieve until safe and efficient means of recycling human nutrients can be implemented. However, considerable potential exists to enhance the cycling of nutrients within cropping systems so that external inputs can be minimized. Davis et al. (2012) suggest that productivity and environmental sustainability can be optimized in a system that is driven by endogenous inputs and “tuned” using small amounts of external inputs.

Endogenous inputs have additional impact on the health of farming systems due to their form, in addition to their source. C-based nutrient sources, such as animal manure and green manure crops, are known to increase abundance and diversity of soil fauna and to enhance plant health and resistance to pests by preventing excesses of free amino acids in plants (Phelan 2009). In addition, use of diverse nutrient inputs, including organic residues and BNF, builds more stable reservoirs of nutrients in soil, reducing losses to the environment (Drinkwater and Snapp 2007).

Animal Manure and Compost
Use of animal manure as a nutrient source for crops has diminished with the separation of crop and livestock production systems and the availability of easy-to-use synthetic fertilizers (Davis et al. 2012). As a result, animal manure is often treated as a waste product rather than as a source of fertility and organic matter for cropping systems. However, recognition of the beneficial effects of livestock manure is growing, along with awareness of how to mitigate potential water and air quality issues.

Many studies have observed excellent crop response to manure application, with yields often equal to or near the yield obtained with synthetic fertilizers (Blackshaw 2005; Miller et al. 2009; Olson et al. 2010; Buckley et al. 2011). Much of the benefit to crops is through nutrient supply, but non-nutrient benefits are also important. In a moisture-limited growing season in Utah, application of composted manure increased the moisture retention capability of soil, improving yield (Stukenholtz 2002). In Saskatchewan, crops grown in cattle or hog manure-amended soils had better vigour and were less affected by common root rot (de Freitas et al. 2003).

Manure application to farmland also enhances soil C, microbial biomass, microbial activity, and populations of nematodes and natural enemies of crop pests (de Freitas et al. 2003; Snapp et al. 2010; Garratt et al. 2011; Hu and Qi 2011; Moulin et al. 2011). Carry-over effects on crop yield and other benefits to subsequent years are also commonly observed (e.g., Endelman et al. 2010). Reeve et al. (2012) observed positive effects on crop yield, soil organic C, and microbial biomass 16 yr after compost application in dryland wheat.

Manure application at high rates and/or frequency can result in nutrient accumulation in soils, contamination of surface and ground water, and increased GHG emissions (Stumborg and Schoenau 2008; Ashjaei et al. 2010; Miller et al. 2010, 2011, 2012). Appropriate management practices such as those described by Schoenau and Davis (2007) and others can effectively mitigate the potential for nutrient loss and environmental contamination. Nutrient build-up can be prevented by applying manure to meet the P, rather than N, requirements of the crop or haying manure-amended grasslands rather than grazing (Olson et al. 2010; Wilson et al. 2011). Including a high-C substrate, such as wood chips, in manure can also reduce N loading to the system (Miller et al. 2011). Incorporating manure into soil reduces volatilization of N (Schoenau and Davis 2006) and nutrient losses to surface water (Jokela et al. 2012). Even though N leaching from manure and compost can occur, it is often less than leaching from synthetic fertilizers, even when total N inputs are equal to or higher than synthetic N inputs (Pimentel et al. 2005; Snapp et al. 2010).

While the mixed-farm model provides the simplest framework for recycling manure nutrients back to crops, improved manure processing and application practices allow for novel approaches to using manure on cropland. Transporting liquid manure long distances is energy intensive (Wiens et al. 2008) and has prompted research on methods to separate solid and liquid components of liquid manures (e.g., Fangueiro et al. 2012; Xia et al. 2012) and on the agronomic effects of the resulting components (e.g., Bittman et al. 2011). Implements for improved application of solid manure are also being developed (e.g., Laguë et al. 2006). Composting manure may enhance its agronomic and soil health benefits (Lynch et al. 2005).

Green Manures and Biological N Fixation
Biological nitrogen fixation by legumes currently provides only about 18% of N inputs in Canadian agriculture [calculated from Janzen et al. (2003)]. Thus, there is considerable potential to explore agricultural systems that make better use of legumes for BNF.
Perennial forages and annual green manure crops offer the greatest potential for soil enrichment with N, while grain legumes and short-duration cover crops can contribute smaller amounts of N to the system. Along with N fixation, legume green manures in rotation add organic matter, cycle other nutrients, suppress weeds, disrupt pest cycles, and enhance soil physical, chemical, and biological properties (Fageria 2007).

The yield of crops following legume green manure crops depends largely on biomass production (and associated N fixation and subsequent mineralization) of the green manure. In moisture-limited regions, water use by the green manure crop may also be a major factor. An annual legume green manure such as black lentil (cv. Indianhead), chickling vetch (Lathyrus sativus L.), field pea, or hairy vetch can typically contribute 50–150 kg N ha⁻¹ in the Canadian prairies, depending on green manure species and biomass production (Bullied et al. 2002; Thiessen Martens and Entz 2011; Vaisman et al. 2011). Early termination of green manures where moisture is limiting effectively optimizes water availability to the following crop and N fixation by the green manure (Zentner et al. 2004; Allen et al. 2011). In semiarid environments, where green manure biomass production is relatively small, it may take several crop rotation cycles for a legume green manure to accumulate sufficient N to produce yields equal to fertilized treatments (Zentner et al. 2004; Allen et al. 2011). Green manures also enhance many soil biological parameters, including populations of soil bacteria and fungi, soil microbial biomass N and C, and microbial activity (Biederbeck et al. 2005).

The economics of green manures in rotation compared with synthetic fertilizer use depend largely on the price of fertilizer, green manure establishment costs, and the yield benefit realized due to the green manure. In a study where green manures were produced in place of summerfallow, reductions in fertilizer requirements more than offset the cost of green manure establishment after several crop rotation cycles with good soil water management practices (Zentner et al. 2004). However, in continuous cropping systems, green manure production requires farmers to forfeit a year of cash crop production, negatively affecting the economics of the system. Obtaining some direct economic value from a green manure crop through grazing (Thiessen Martens and Entz 2011) or seed harvest (Chen et al. 2012) can improve net returns, although seed harvest reduces subsequent crop yields (Chen et al. 2012).

**Soil Biological Fertility**

Soil biological fertility links a healthy soil with the ability to deliver nutrients to plants and is defined as “the capacity of organisms living in soil (microorganisms, fauna and roots) to contribute to the nutritional requirements of plants and foraging animals for productivity, reproduction and quality... while maintaining biological processes that contribute positively to the physical and chemical state of the soil” (Abbott and Murphy 2007). Soil biological fertility is still poorly understood but is seen as an important contributor to the sustainability of agricultural systems due in part to more balanced plant nutrition and lower risks of nutrient loss (Drinkwater and Snapp 2007; Phelan 2009).

Organic matter additions (crop residue, farmyard manure, and green manure), legume-containing pastures, diverse crop rotations and crop mixtures, minimum or no-till systems, livestock grazing, and application of certain inoculants are known to enhance soil biological fertility, with positive effects on chemical and physical attributes of soil as well; tillage and application of fertilizers and pesticides, on the other hand, generally inhibit soil biological activity (Abbott and Murphy 2007; Clapperton et al. 2007; Nelson and Spaner 2010; Druille et al. 2013). Crop diversity appears to be one of the most important contributors to soil biological fertility (Drinkwater and Snapp 2007). Nelson and Spaner (2010) conclude that both no-till farming systems that limit inputs and organic farming systems that limit tillage could create conditions that favour soil biological fertility, if crop diversity is high (i.e., including cover crops and intercrops).

Developing management practices that promote specific plant nutrition goals is difficult due to our limited knowledge of soil microorganisms and their function, as well as the dynamic and site-specific nature of soil biological fertility (Abbott and Murphy 2007). Investigations into the role of soil biological activity in crop uptake of P, for example, have produced varying results. There is evidence that soil–plant–microbe interactions can enhance P uptake by plants through more thorough soil exploration (i.e., through hyphal networks of mycorrhizal fungi) and/or enhanced P solubility due to root exudations and associated effects on enzyme activity or soil pH (Marschner and Rengel 2007; Conyers and Moody 2009). This effect has been observed in a long-term organic-conventional comparison study in Manitoba, where flax (Linum usitatissimum L.) grain P concentration was higher in organic production systems that had lower plant-available P and higher levels of mycorrhizal colonization than in conventional production systems that had higher soil P and lower levels of mycorrhizal colonization (Entz et al. 2004; Welsh 2007; Welsh et al. 2009). Others have observed net negative impacts of mycorrhizal colonization on organic wheat yield due to excessive C demand by the mycorrhizal fungi on the crop (Dai et al. 2014). Based on a review of Australian literature, Ryan and Kirkegaard (2012) indicate that crop production practices to enhance mycorrhizal colonization are not generally effective in Australia, but may be worth exploring in regions such as Canada, where more mycorrhizal crops are grown. Drinkwater and Snapp (2007) suggest that loss of diversity and function in microbial communities due to current agricultural practices may have caused a shift.
in some plant–microbe interactions from mutualistic to parasitic relationships.

**Organic Systems**

Organic farming is a system that relies heavily on endogenous inputs. While a range of practices is permitted under the Canadian organic production standards, there is a clear emphasis on environmental sustainability and ecological integrity [Canadian General Standards Board (CGSB) 2006].

In the Canadian prairies, organic farmers typically manage soil fertility through crop rotation, green manures, forages in rotation, and manure or compost applications, while weeds are generally managed through cultural means such as high seeding rates or mechanical means such as tillage (Nelson et al. 2010). Average wheat, oat, barley, and flax yields on 14 organic farms in the eastern prairies were 73–78% of the long-term conventional average yields (Entz et al. 2001), in agreement with a recent meta-analysis (Seufert et al. 2012). According to surveys of organic farmers in the Canadian prairies, crop rotations, soil fertility and health, and weed management are the major production challenges (Frick et al. 2008; Organic Agriculture Centre of Canada 2008a, b).

Despite lower yields, organic production systems are associated with a number of benefits. Organic systems promote biodiversity in a wide range of faunal groups including arthropods, soil biota, and farmland birds, with some direct enhancement of ecosystem services such as pest predation and pollination (Morandin and Winston 2005; Crowder et al. 2010; Garratt et al. 2011; Power et al. 2012; Winqvist et al. 2012). Organic systems have lower ecological footprints (Bavec et al. 2012), have increased energy efficiency (Hoepner et al. 2006; Zentner et al. 2011b), and enhance a number of soil and nutrient parameters such as soil C and nutrient retention (Pimentel et al. 2005). Increased soil organic matter in organic systems can also contribute to improved crop yield in years of moisture deficiency (Stokenholtz 2002; Lotter et al. 2003). Organic inputs in the form of livestock manure or compost support both the productivity and sustainability of organic systems. Manure/compost additions enhance yields of organic crops (Pimentel et al. 2005; Bavec et al. 2012) and have been observed to build up soil C (54% increase) and reduce N leaching (50% reduction) compared with systems using synthetic fertilizers (Snapp et al. 2010).

Economic analysis of organic vs. conventional farming systems has shown that organic systems are often economically competitive with conventional systems due to their lower input costs, premium prices for products, direct marketing opportunities, and resilience to weather extremes (MacRae et al. 2007). In long-term experiments in Saskatchewan, Minnesota, and Iowa, organic systems had net returns greater than or equal to conventional systems, but these levels of return were dependent on organic premiums for at least some crops (Delate et al. 2003; Delbridge et al. 2011; Zentner et al. 2011a). Income variability may be lower in organic systems (Pimentel et al. 2005; Zentner et al. 2011a).

The value of organic farming to long-term sustainability of agricultural systems is often hotly debated; this discussion tends to focus on the (lack of) productivity of organic systems versus the environmental damage and reliance on external inputs of conventional systems. The range of farming practices employed in both organic and conventional farming systems makes categorical comparison extremely difficult but is instructive in determining which aspects of each farming system are beneficial or detrimental. Poorly designed organic farming systems with low productivity tend to deplete soil organic C (Bell et al. 2012; Leifeld 2012) and are thus both unprofitable and environmentally unsustainable. In contrast, well-designed organic farming systems that effectively harness ecological processes are both productive and environmentally sustainable (Halberg 2012). Organic systems also have potential for mitigation of climate change through reductions in N₂O emissions, elimination of synthetic fertilizers, and C sequestration, and for adaptation to climate change through farm diversification, building of soil organic matter, and independence from external inputs (Scialabba and Müller-Lindenlauf 2010).

Nutrient exports in excess of nutrient inputs can result in eventual mining of soil nutrients in organic systems (Welsh et al. 2009). While nutrient cycling in organic systems may be enhanced through the use of manure, crop–livestock integration, and soil biological fertility, it is necessary to close nutrient cycles in agricultural systems more completely to create systems that are sustainable in the long-term. This will require recycling of nutrients contained in human waste, a practice not currently permitted in certified organic systems (CGSB 2006).

**Integrated Crop–Livestock Systems**

The goal of integrating crops and livestock is “integration of function rather than mere diversification” (Schiere et al. 2002). These functions involve nutrient cycling, consumption and “processing” of crop residues, and pest management (for both crops and livestock), among others. The benefits of crop–livestock integration also include increased income and income stability (Franzluebbers and Stuedemann 2007; Russelle et al. 2007) as well as the potential to reduce GHG emissions from both crop and livestock systems (Asgedom and Kebreab 2011). Crop–livestock integration plays a supporting role in other beneficial cropping practices since some techniques, such as growing green manures, cover crops, annual and perennial forages, and agroforestry systems become more financially attractive when livestock products can be gained from the system (Gardner and Faulkner 1991; Clason and Sharrow 2000; Thiessen Martens and Entz 2011; Chen et al. 2012).
While crop–livestock integration is common in perennial forage-based systems, many other possibilities exist. Annual cropping systems offer many opportunities for integration of ruminants, and pigs and poultry can provide unique services such as rooting (tillage) and selective weed grazing or insect predation (Entz and Thiessen Martens 2009 and references therein). Ecological functions may be enhanced even further when livestock are integrated into more complex systems such as agroforestry and even aquaculture (Mcadam et al. 2007; Entz and Thiessen Martens 2009; Haile et al. 2010). Optimization of crop–livestock systems in the prairie region requires further exploration of the relationships among soil, crops, uncultivated areas, and livestock, including the role of nutrient transformation and redistribution by livestock, the effects of specific grazing strategies on soil health, and the role of livestock in management of weeds and natural vegetation.

Integration can occur either on a single mixed farm or in a cluster of various types of specialized farms. The most common approach to area-wide integration involves hauling of manure or compost from livestock operations onto surrounding farmland. Another option is to move the livestock onto farmland in custom grazing operations or other arrangements between crop and livestock farmers. Proximity of farms and trust between farmers are keys to the success of such systems (Entz and Thiessen Martens 2009).

Nutrients
The role of livestock in cycling of nutrients, especially N and P, is perhaps the most important reason for crop–livestock integration (Entz and Thiessen Martens 2009). Nutrients in plant material consumed by livestock, especially ruminants, are converted quickly into more plant-available forms, thus accelerating nutrient cycles. Interestingly, the microbial processes responsible for this conversion in the rumen are also more efficient than soil microbial processes (Russelle 1992). With acceleration of nutrient cycles, however, comes increased risk of loss. Thus, crop–livestock systems require careful planning and continual assessment to optimize the use of nutrients.

Integration of crops and livestock can result in semi-closed nutrient cycles. Organic and biodynamic dairy farms in Ontario and Australia had P balances near zero on average; however, nutrient exports in agricultural products can result in a negative P balance even on mixed farms, especially when little or no feed is purchased (Lynch 2006; Cornish 2007). Purchasing feed from off the farm allows for P inputs without using synthetic fertilizers or rock P (Gordon et al. 2002). Knowledge of nutrient concentrations in feed and manure is important for effective management.

Grazing in Annual Cropping Systems
Swath, Bale, and Crop Residue Grazing. Alternative winter feeding systems, in which cattle are fed baled or swathed forages on pasture or cropland or allowed to graze crop residues such as corn stover can reduce overall costs by reducing forage harvest and manure hauling costs (Volesky et al. 2002; McCartney et al. 2004; Karn et al. 2005), if costs associated with watering systems, forage wastage, and checking cattle are not excessive (Nayighugu et al. 2007).

These feeding systems also have potential to enhance nutrient return to farmland and the performance of subsequent crops. In two Saskatchewan studies, soil N and P concentrations, nutrient recovery, and subsequent crop productivity were increased in at least some field locations after bale or swath grazing on annual cropland or grass pasture (Jungnitsch et al. 2011; Kelln et al. 2012). However, bale grazing systems can result in nutrient excesses and risk of environmental contamination at some points (Kelln et al. 2012) as well as elevated nutrient levels in spring run-off (Smith et al. 2011).

Both swath and bale grazing systems can be implemented using annual or perennial forages, on either annual cropland or perennial hay or pasture. Bale grazing offers the potential for nutrient transfer within a system by placing bales in strategic locations such as areas with lower soil fertility.

Green Manure/Cover Crop Grazing. Integrating grazing livestock into green manure or cover cropping systems has potential to improve the economics and thus the adoption potential of BNF by legumes in rotation (Gardner and Faulkner 1991; Sulc and Tracy 2007; Thiessen Martens and Entz 2011). Crops used as annual green manures in the Canadian prairies typically have high forage quality but variable palatability to livestock and tolerance to grazing (Marten 1978; Gardner and Faulkner 1991; Miller and Hoveland 1995; Fraser et al. 2004). Certain negative effects on animal health associated with grazing legume green manures, cereals, or brassicas have been observed (Gardner and Faulkner 1991; Johnson et al. 1992; Panciera et al. 1992; Hannaway and Larson 2004; Rao et al. 2005; McCartney et al. 2008, 2009; McCartney and Fraser 2010); however, animal health risks posed by grazing can generally be minimized through crop cultivar selection and grazing management.

While research into these systems is limited, results indicate that crop yields following grazed green manures are equal to those following green manures that were not grazed (Franzluwebers and Stuedemann 2007; Cicek et al. 2014b, c). Grazing can, however, increase N availability in the soil in the fall, creating N leaching potential; fall catch crops may be useful for preventing N leaching following grazed green manures (Cicek et al. 2015).

The effects of grazing cover crops on soil health are a major motivator for those producers who are using this system. Fraase et al. (2010) reported that soil bulk density decreased from 2009 to 2010 where turnip (Brassica
campestris var. rapa Linn.) and “cocktail” cover crops were produced and grazed. In other regions, researchers have found that grazing increased soil microbial biomass (Franzluebbers and Stuedemann 2008a) but had no effect on bulk density or soil aggregate stability (Franzluebbers and Stuedemann 2008b).

**Farmscaping**

Farmscaping refers to the “modification of agricultural settings, including management of cover crops, field margins, hedgerows, windbreaks, and specific vegetation growing along roadides, catchments, watercourses, and adjoining wildlands” (Bugg et al. 1998). In farmscaping, the role of landscape pattern and diversity in providing benefits to agricultural systems is central. Common farmscaping techniques include establishment of areas of perennial vegetation and protection and management of riparian zones and small-scale wetlands (Long and Pease 2005; Smukler et al. 2010). While farmscaping can be implemented in any farming system, Kirschenmann (undated) argues that mid-sized farms are better than large farms at preserving wildlife habitat, and Garratt et al. (2011) and Halberg (2012) suggest that organic farms tend to have a higher degree of landscape diversity due to smaller field size and an inclination to preserve natural areas. Better understanding of the role of landscape-scale processes and landscape features is necessary to develop farmscaping practices that optimize the relationships between cropland and uncultivated areas.

The benefits of farmscaping to agricultural systems are largely due to enhanced associated biodiversity, specifically of beneficial organisms including wild pollinators and natural enemies of crop pests (e.g., Garratt et al. 2011; Morandin and Kremen 2013), as a result of planned biodiversity (Altieri and Nicholls 2008; Liebman and Schulte 2015). Additional benefits of these permanent landscape features can include other ecosystem processes such as nutrient cycling, soil C sequestration, capture of sediment and nutrients in run-off, water filtration, and enhancement of the local and regional water cycles (van de Kamp and Hayashi 1998; Pretty 2008; Smukler et al. 2010; Gleason et al. 2011; Liebman and Schulte 2015); provisioning services such as fruit or forage production from these landscape features themselves (Zink 2010); and increased productivity from surrounding cropland (Morandin and Winston 2006; Liebman and Schulte 2015). Disproportionately large ecological benefits may be realized by converting small areas of cropland to herbaceous perennial vegetation, creating unique habitats throughout the farm, or using a few key species of woody plants in the farm landscape (Smukler et al. 2010; Liebman and Schulte 2015).

Opportunities for farmscaping in Canadian prairie farming systems include strategic development and management of riparian buffer zones, field shelterbelts and ecobuffers, and agroforestry systems. An opportunity exists in irrigated crop production utilizing centre pivots where unirrigated field corners could be planted to perennial herbaceous or woody vegetation (Zink 2010). In addition, natural and constructed wetlands, both permanent and ephemeral, provide crucial habitat for waterfowl (Shutler et al. 2000) and capture soluble nutrients lost from elsewhere in the system (Drinkwater and Snapp 2007).

In many cases, the benefits of farmscaping are difficult to quantify in economic terms. However, an example from northern Alberta indicates that increased yield of canola in close proximity to uncultivated areas would more than offset the cost of taking this land out of cultivation, due to better pollination and seed set (Morandin and Winston 2006).

**ASSESSMENT OF FARMING PRACTICES FOR THEIR ROLE IN THE SUSTAINABLE DEVELOPMENT OF CANADIAN PRAIRIE CROPPING SYSTEMS**

The farming practices reviewed in this paper range from relatively simple modifications to the types of systemic changes suggested by Gliessman (2010). While some practices are well understood and established in practice (e.g., crop rotation, no-till), others are in their infancy and require more research and development (e.g., soil biological fertility, farmscaping). In many cases, we do not have complete knowledge of the impacts of particular practices on specific criteria related to profitability, sustainability, and resilience, especially for the Canadian prairie region, nor do we fully understand the interactions among practices and components or the relative importance of various criteria. Thus, it is difficult to compare the net impact of these practices. However, it is possible, based on the literature already discussed, to identify some general characteristics of agricultural systems that tend to be profitable, sustainable, and resilient and to evaluate the practices described in this review based on how closely they adhere to the principles that support these characteristics.

Agricultural systems that most closely mimic natural systems appear to be the most resilient and environmentally sustainable due to their biological and enterprise diversity; integration, multifunctionality, and redundancy among components; effective nutrient cycling through promotion of soil biological activity and minimal use of external inputs; leveraging of natural ecosystem processes; and minimal soil disturbance (Lin 2011; Malézieux 2012). Diversity lends stability (both ecological and economic) and effective integration of system components builds integrity and allows for realization of synergies among processes (Elton 1958; Altieri 1999; Gliessman 2010; Malézieux 2012). Profitability of such systems will depend in part on the choice of agricultural species and optimization of synergies among components. It is important to note that these ecologically based whole farm systems have not yet received much research attention and, therefore, have the most uncertainty associated with them. Given their potential benefits, they
deserve significantly more research and development attention.

Based on these characteristics, farmscaping, crop–livestock integration, agroforestry, perennial forages, and perennial grains, complemented with endogenous input systems and minimal soil disturbance, have the potential to make large contributions to sustainability and resilience. When such systems are designed to comply with organic production standards, market premiums further enhance their profitability. Perennial forages in particular have a large and well-documented positive impact on environmental sustainability and resilience and are also technically feasible. While perennial grain systems appear promising, implementation of such systems is impossible until varieties become commercially available. Applied research on integrated crop–livestock systems, alley cropping, and farmscaping (including shelterbelts and ecobuffers) is needed to optimize and support implementation of these practices in the prairie region. Local farmer knowledge of crop–livestock systems and farmscaping practices may be more developed than local research in these areas, as ecologically minded farmers make observations and experiment with practices on their own farms.

Profitability, sustainability, and resilience can be enhanced to some degree by adding diversity to annual cropping systems without a major change in the system. Practices that can be implemented relatively easily within annual cropping systems include crop selection and rotation, cover crops, reducing tillage, animal and green manures, soil biological fertility, annual polyculture, and crop varieties and genetics. Even these practices have challenges associated with their implementation. For instance, optimal use of crop rotation may be limited by poor markets for all but a few crops, which causes farmers to shorten their rotations, and the sustainability of no-till farming is limited by its reliance on herbicides. Finding a temporal niche for cover crops in the short growing season of the prairies remains a challenge, but novel ways of including and using cover crops, perhaps in integrated crop–livestock systems, would increase the adoption potential and realized benefits. A shift to the use of endogenous inputs in cropping systems requires greater knowledge of how to manage these systems effectively. While some of these practices individually may have a relatively low impact on sustainability, profitability, and resilience, they remain useful during the transition to redesigned integrated systems and are important components of fully redesigned systems (Gliessman 2010).

The challenges associated with implementing individual diversification practices highlight the importance of taking a holistic, integrated approach to designing agricultural systems. This ecological approach to agriculture involves using nature as a model to guide the design and management of farming systems, with particular attention to the structures and processes occurring in natural systems and adaptation to local conditions (Malézieux 2012). Sustainable agricultural systems depend on ecological processes that promote qualities such as soil fertility, pest resistance, pollination, and productivity, but also on social processes that generate knowledge and incentives for producing a variety of food and fibre using locally affordable methods. Thus, a truly ecological approach to agriculture is one that links ecology, culture, economics, and society to sustainable agricultural production, healthy environments, and viable food and farming communities that are able to adapt to change and persist in the long-term (Gliessman 2010; Cabell and Oelofse 2012).

Ecological agriculture may encompass many or all of the practices already discussed in this paper and, as such, may realize the benefits attributed to individual practices. More importantly, an integrated approach to developing a whole farm system can also create synergies among individual practices and enhance the benefits to the system, if diverse components are “correctly assembled in space and time” (Altieri 1999) with attention to integration of function (Schiere et al. 2002). Researchers in Minnesota determined that highly diversified and ecologically integrated farm operations and landscapes would provide greater economic, environmental, and social benefits than systems employing a set of best management practices (Boody et al. 2005). Intensification of ecological farming systems through careful management of biological processes may allow for high levels of both food production and ecosystem services (Doré et al. 2011).

Our understanding of ecological processes in agriculture is still poorly developed and the application of concepts in location-specific recommendations is often lacking. Because agroecological systems are to be modelled after the native ecosystems of the region, local research to develop these systems is needed around the world and, specifically, in the various ecozones of the Canadian prairies.

CONCLUSION

This review demonstrates that agricultural systems designed according to ecological principles and local ecologies contribute to better outcomes for the agricultural systems of the Canadian prairies. We have argued that these systems require systemic change if profitability, sustainability, and resilience are to be optimized. Just as the key ecological pillars of diversity and integration lend stability and integrity to ecosystems, integrating diverse components in ecologically compatible complementary relationships within supportive economic and social structures promotes the overall health of the system, including environmental sustainability, long-term profitability, and resilience to shocks and stresses. Thus, system change requires purposeful and proactive redesign of agricultural systems at all levels, from individual farms to regional and even global scales, with particular attention to functional integration of diverse components.
The challenge to align Canadian prairie agricultural systems with ecological principles is immense, especially in the current context of agricultural development where short-term productivity and economic efficiency are emphasized. However, the more holistic goals encompassed in ecologically based systems are fundamental to the long-term success of any sector or society and are worthy of serious pursuit. Past government and university scientists in the prairies have also called for system redesign with a shift to “permanent agriculture” based on diversified crop rotations and effective crop-livestock integration (Janzen 2001). Had our agricultural policy makers, educational institutions, and businesses embraced this advice, we would be much further ahead than we are today. We believe that locally adapted ecological prairie farming systems are still achievable but will require a major shift in research, education, and policy. A proactive move in this direction would provide a solid foundation for the development of environmentally sustainable, profitable, and resilient agricultural systems in prairie Canada.


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