Ecological Farming Systems on the Canadian Prairies

A Path to Profitability, Sustainability and Resilience

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Executive Summary

In the face of global and regional drivers affecting the context in which Canadian agricultural systems function, it is important to consider how the Canadian agriculture sector should evolve and develop to thrive economically while protecting our natural resource base and building resilience.

Current cropping systems in the Canadian prairie region are based predominantly on simplified, monoculture-based, input-driven production of annual crops, a model which has resulted in the development of unintended negative consequences such as loss of soil organic matter, contamination of the environment with escaping nutrients and pesticides, and major losses of both agricultural and natural biodiversity. Ecologically-based farming systems are an alternative to the prevailing system of annual monoculture. Such systems rely on the use of ecological processes to support agricultural production, while reducing reliance on external inputs and providing a level of economic stability.

The objective of this paper is to evaluate a wide range of ecologically-based farming practices and systems for their potential role in enhancing the profitability, environmental sustainability, and resilience of cropping systems in the Canadian prairie provinces. Management practices are described and then assessed against a selection of criteria within these three categories, as well as some operational criteria, to identify practices that hold immediate potential for significant impact through widespread implementation, as well as practices that have high potential but require more development and/or research. The farming practices discussed fall into the following categories: 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 farmscaping.

Organic systems, perennial forages in rotation, perennial grains, integrated crop-livestock systems and farmscaping are identified as practices with the highest potential for positive impacts on environmental sustainability, profitability and resilience. However, lack of knowledge on specific, locally adapted management practices limits the current technical feasibility and adoptability of many of these systems. Other well-understood and widely implemented practices such as crop rotation, no-till systems, and shelterbelts have moderately high potential for positive impacts, which could be further enhanced through an integrated, ecological approach to agricultural systems. Practices with the lowest expected impact on assessment criteria are crop varieties and genetics and annual polyculture.

A shift to ecologically-based agricultural systems as a framework in which to place all other farming practices is identified as a high priority for development of prairie farming systems. Transitioning to such systems would require support for farmers in the form of incentive and risk management programs, educational programs and demonstration projects, and long-term interdisciplinary research programs focusing on local adaptation of ecological farming systems.

INTRODUCTION

Canadian agricultural systems are currently faced with a number of global and regional drivers that have the potential to dramatically change the context in which these systems function. Producing primarily commodities for export markets, the agricultural systems of the Canadian prairie region are affected by global forces such as population growth, geopolitical instability, world weather patterns and grain stocks, and the rise of middle power nations such as China, India and Brazil. Rising energy and input costs, urbanization and competition for natural resources, and advances in digital and other technologies are changing the way prairie farms operate. Consumer trends such as changing diets worldwide and the desire for safe, nutritious and environmentally friendly foods impact the demand for specific products and production methods. Meanwhile, the productive capacity of Canadian prairie farms is threatened by extreme weather (e.g. floods, droughts), growing incidence of crop diseases and pests, and difficulty controlling herbicide resistant weeds. The impacts of agriculture on biodiversity, water quality, and greenhouse gas emissions are also of concern to a public that is becoming ever more aware of environmental issues.

All these factors, among others, are having and are expected to increasingly have significant implications for the growth, sustainability and resilience of Canadian agricultural systems. Thus, it is important to consider how the Canadian agriculture sector should evolve and develop to thrive economically while protecting our natural resource base and building resilience in this dynamic context.

Past agricultural development has tended to focus on the productivity of the system, without regard for external costs to the environment or the multi-functionality of agricultural systems (Pretty, 2008). This departure from traditional agricultural systems based on ecological processes has been justified by the "need" to maximize production for the sake of feeding a growing global population. However, it is becoming increasingly apparent that the costs of industrial agriculture are significant and that environmental and social criteria should be included when assessing the merits of any agricultural production system or approach.

Current cropping systems in the Canadian prairies are based predominantly on monocultures of annual crops, constituting a major departure from the native ecosystems of this region. In fact, the characteristics of agricultural systems are remarkably similar to the characteristics of dysfunctional or highly stressed ecosystems (Phelan, 2009). Production of annuals on a large scale requires constant and widespread disturbance (either mechanical or chemical) to maintain the system in the earliest successional state and production of monocultures results in low genetic diversity and poor niche utilization. Mechanical disturbance (tillage) also results in exposed soil and oxidation of soil organic matter. These negative effects on soil health are exacerbated by the removal of crop biomass (i.e. carbon (C)-based inputs) from the land. Nutrient cycles are very different in agricultural systems than natural systems, due to reliance on synthetic nutrient formulations rather than recycling of nutrients within the system. Separation of crop and livestock components of agriculture has also compromised nutrient cycles, resulting in nutrient deficiencies in cropping systems and nutrient excesses in livestock systems. Large-scale production of a small number of annual crops, highly effective chemical weed control, and conversion of natural areas to cropland have drastically reduced both agricultural and natural biodiversity in the Canadian prairies, thus compromising ecosystem

services such as natural pollination and increasing vulnerability to environmental stresses and shocks.

Several issues arise as a result of our current approach to agriculture, bringing into question the sustainability of this approach. It is widely recognized that annual cropping is responsible for major losses in soil organic matter and widespread soil erosion. Contamination of the environment with escaping nutrients and pesticides, over-use of water, loss of both agricultural and natural biodiversity, salinization and compaction, and reliance on external inputs of non-renewable resources have also been identified as major areas of concern (Pretty, 2008; Halberg, 2012; Kremen and Miles, 2012).

Along with issues of environmental sustainability, the reduction in the number of farms in Western Canada in recent decades is a startling reminder of the difficulty that farmers face in staying in business or starting into farming. While gross revenues have steadily increased over the last 50 years, so have the costs of production, resulting in net farm revenues that are similar to those earned 50 years ago. Escalating costs of production are driven chiefly by reliance on external inputs.

In response to the evident unsustainability of simplified, monoculture-based, input-driven cropping systems, a variety of ecologically-based farming systems have been proposed and developed as alternative models. Ecologically-based farming systems seek to treat the farm as an ecosystem in which soils, plants, and animals interact in ways similar to those in natural ecosystems, albeit with human management. They are founded on ecological concepts and processes such as biological, functional and structural diversity, nutrient and energy cycling, advancement of successional states, and balanced predator-prey relationships. This ecological approach to agriculture maintains biological functions and ecosystem services within farming systems, supporting agricultural production through processes such as nutrient cycling, maintenance of soil quality, pest management and pollination. In these systems, the need for external inputs is reduced and biological diversity and ecological functional redundancies create a level of natural resilience to stressors. In addition, the farm enterprise diversification associated with ecologically-based farming is commonly considered beneficial for income stability and mitigation of economic risk. Therefore, ecological farming systems appear to have considerable potential as a model for agricultural development in western Canada.

There is a growing body of research on farming practices that can contribute to the development of ecologically-based cropping systems for the Canadian prairies. These include practices that are already implemented in this region on a limited scale as well as others that are well understood in other regions but require application in the prairie climate. For some, the value of the concept is well established but specific management practices are lacking. The objective of this paper is to evaluate a wide range of these agroecological practices and systems for their potential role in enhancing the profitability, environmental sustainability, and resilience of cropping systems in the Canadian prairie provinces. Key focus areas include diversified crop production systems, reduced tillage, nutrient cycling through endogenous input systems, integration of crops and livestock, and farmscaping.

DEFINING AND ASSESSING PROFITABILITY, SUSTAINABILITY AND RESILIENCE IN CROPPING SYSTEMS

In the quest for better agricultural practices, many workers have attempted to develop assessment approaches that evaluate the contributions of these practices to the overall betterment of the system. Many of these approaches are framed in terms of "sustainability", "agroecosystem health" or "resilience" and many include both ecological and social components (e.g. Xu and Mage, 2001; Darnhofer et al., 2010; Cabell and Oelofse, 2012). The assessment criteria established in these studies vary widely and many authors agree that one of the major difficulties in this task is to define appropriate criteria and develop effective ways of measuring agricultural system performance (Darnhofer et al., 2010; Cabell and Oelofse, 2012; Koohafkan et al., 2012). Nonetheless, the themes of profitability, sound environmental practice (sustainability) and resilience (both ecological and social) recur throughout the literature on this topic and provide a basic framework for evaluating our farming practices in the short-, medium- and long-term time frames required to assess the health of our agricultural systems. Articulation of clear and workable definitions of these areas and the factors that contribute to them is key to the development of such holistic measures of success.

We have selected a number of criteria within the categories of sustainability, profitability, and resilience that are relevant to prairie cropping systems against which to assess a wide variety of agricultural practices. We also assess each practice against some operational criteria to determine how easy each practice may be to implement. The assessment criteria are described in detail in Table 1.

Environmental Sustainability

Sustainability has become a ubiquitous term and has been defined in many ways, ranging from the simple ability to continue a particular practice into the future to complex measures of ecological function and social dynamics. For the purposes of this paper, we use the definition of sustainability provided by Jules Pretty (2008): "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". The ability of an ecosystem to provide these services is a function of the ecological integrity of the system. Therefore, sustainable agriculture practices must be based on biological and ecological processes, principally the interactions between soils, crops and animals; in addition, sustainable agricultural practices minimize the use of non-renewable inputs and are rather based on knowledge and skill and the capacity of people to work together (Pretty, 2008; Koohafkan et al., 2012; Malézieux, 2012). More specifically, sustainable agricultural systems minimize nutrient losses, 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).

Key environmental criteria considered in this paper include soil health, protection of soil from erosion, effective soil water management, water and air quality protection, effective nutrient management, natural pollination and pest and disease suppression services, reductions in greenhouse gas emissions and enhanced C sequestration (Table 1).

Table 1. Description of sustainability, profitability, resilience and operational criteria for assessment of farming practices for their potential role in Canadian prairie cropping systems.

Criteria	Description	Rating Question
Sustainability Criteria		
Soil Health	Soil health refers to the capacity of a soil to be used productively without compromising future productivity or the environment. It includes biological, chemical and physical characteristics of soil including: organic matter, infiltration, aggregation, pH, microbial biomass, respiration quotient, forms of nitrogen (N), bulk density, topsoil depth, conductivity or salinity, available nutrients.	To what degree is the management action, practice or approach likely to increase soil health?
Soil Erosion	Soil erosion on agricultural land can impact both short and long term productivity by removing critical nutrients and negatively affecting the physical structure of the soil (AAFC, 2007). On the Canadian Prairies, 5% and 36% of agricultural land is at high to severe risk of erosion by water and wind, respectively (AAFC, 1995).	To what degree is the management action, practice or approach likely to reduce soil erosion?
Dewatering Wet Soils	In regions with high rainfall and/or heavy textured soils, dewatering wet soils can be agriculturally desirable. Wet soils associated with wetlands habitats provide important ecosystem services, often of direct value to agriculture, and their dewatering is generally considered undesirable.	To what degree is the management action, practice or approach likely to result in a desirable reduction of soil water on farm?
Storing Water in Dry Soils	In areas that typically receive relatively low levels of moisture relative to cropping requirements, a reduction in growing season precipitation or lack of timely rain may threaten the viability of dryland crops. In these areas, water capture, storage and conservation in soil can be critical to maintaining the productive capacity of soils.	To what degree is the management action, practice or approach likely to increase a desirable capture and storage of water on farm?
Water Quality Protection	Agricultural management actions, practices and approaches have the potential to improve or degrade surface and ground water quality. Risks to water quality are generally associated with the transport of nutrients, sediments or pathogens.	To what degree is the management action, practice or approach likely to reduce nutrients, sediments or pathogens entering surface or ground water?
Air Quality Protection	Agricultural management actions, practices and approaches have the potential to degrade air quality through ammonia and other related volatiles associated with confined feeding operations (CFOs) and land application of manure, as well as dust and other particulates associated with CFOs, field operations, soil erosion, and burning.	To what degree is the management action, practice or approach likely to reduce the amount of air pollutants emitted?
Ecological Nutrient Management	Natural ecosystems are characterized by closed-loop nutrient cycles mediated by detrital food webs, resulting in synchrony of nutrient release and plant uptake and recycling of nutrients within the system. Agricultural systems inherently require some nutrient export but can still function as semi-closed systems relying on ecological nutrient cycles.	To what degree is the management action, practice or approach likely to cycle nutrients in a manner similar to natural ecosystems?

Criteria	Description	Rating Question
Natural Pollination Services	Natural pollination services refers to pollination of agricultural crops provided by wild pollinators, including bees, flies, wasps, butterflies and birds. These services are necessary for maintaining yields of many food crops (Garibaldi et al., 2013). Agricultural management practices can adversely affect wild pollinator populations by reducing the abundance and diversity of accessible forage (i.e., flowers), nesting sites and resources and through mortality and loss of fitness due to pesticide contamination. Preservation of natural habitat and landscape heterogeneity create positive effects on wild pollinators.	To what degree is the management action, practice or approach likely to increase wild pollination services available to the farm?
Natural Pest Suppression Services	Populations of natural enemies – species that predate or parasitize crop pests – are increased through provision of alternate food sources, refugia from farming activities, and sites for overwintering and aestivation. Agricultural management practices that affect microclimatic conditions such as temperature and humidity can make conditions less favourable to pests. Furthermore, trees and shrubs can mask or diminish the chemical cues that attract pests to a target crop, or act as a 'trap crop' by attracting pests away from the target crop (Altieri and Nicholls, 2004).	To what degree is the management action, practice or approach likely to increase natural pest suppression services available to the farm?
Natural Disease Resistance	Pathogens spread more easily and epidemics are more severe when host organisms are more uniform and abundant. Biological diversity, and particularly genetic diversity, can play an important role in reducing the vulnerability of agriculture to pest and disease outbreaks. Susceptibility to invasion by disease also depends on species composition, disturbance (i.e., stressed communities having less energy available for disease resistance) and other factors.	To what degree is the management action, practice or approach likely to increase the resistance of crops and livestock to diseases or pathogens?
Greenhouse gas emissions	Greenhouse gas emissions contribute to global warming and climate change. Major agricultural sources of greenhouse gases include burning of fossil fuels, methane emissions from livestock and nitrous oxide emissions from soils.	To what degree is the management action, practice or approach likely to reduce greenhouse gas emissions?
Carbon storage/ sequestration	Carbon (C) sequestration in soil and biomass is considered to be an effective approach to offsetting greenhouse gas emissions, thereby mitigating climate change. Major C sinks include perennial crops, trees, and permanent vegetation in natural areas such as wetlands and riparian zones. Reducing tillage may also increase soil C storage.	To what degree is the management action, practice or approach likely to increase C sequestration?

Profitability Criteria

Profitability	Profitability can be increased by either producing more of something that is marginally profitable, increasing revenue for each unit produced or by reducing the cost per unit of production. Practices that allow for reduced inputs while maintaining yield and quality or that enhance yield and quality with the same level of inputs are desirable.	To what degree is the management action, practice or approach likely to increase the profitability of an existing production system or of the entire farm operation?

Criteria	Description	Rating Question
Protectable Advantages	Protectable advantages refer to market positions that are both profitable and difficult for rivals to imitate. Increasingly, agriculture is a knowledge-based economy, but innovations, such as new varieties and production techniques can often be readily imitated by competitors. This process of imitation has been accelerated by globalization and standardization of production practices. Thus, there are significant long-term economic advantages for farmers to develop products, processes, knowledge, markets and/or relationships that are difficult to competitors to imitate. A crop that is particularly well suited to grow in specific locale is a ready example of a protectable advantage. Others relate to local industrial clusters where value-chains are tightly aligned and benefit from proximity to one another and strong inter-personal relationships based on a sense of community (Porter, 1998).	To what degree is the management action, practice or approach likely to create a protectable advantage?
Income stability / reduced risk	Income stability over years and effective risk management are important for the long-term economic success of farms. Enterprise diversity contributes to both risk management and income stability.	To what degree is the management action, practice or approach likely to result in lower risk and/or more stable farm income?

Resilience Criteria

Criteria	Description	Rating Question
Resilience to Climate Extremes	In the context of climate change, increasing climate variability and frequency of extreme climate and weather events are expected in the future. Management practices are considered less vulnerable to climate change if they foster more drought resistance, are less affected by flood events and more resistant to late spring or early fall frosts and extremes in growing degree days.	To what degree is the management action, practice or approach likely to reduce the vulnerability of the farm to climate extremes?
Energy Use/ Efficiency	Conventional agricultural is highly dependent on fossil fuels for many of its inputs and as a substitute for labour. Chemical fertilizers, synthetic pesticides and diesel are key inputs based on non-renewable energy sources. The cost of these inputs has been steadily rising in recent years and is expected to continue to do so. Thus, dependency on non-renewable resources makes agricultural operations vulnerable to economic forces beyond their control and reduces their overall resilience.	To what degree is the management action, practice or approach likely to reduce on-farm energy use or increase on-farm energy efficiency?
Enterprise Diversity	In the context of Canadian agriculture, resilient systems are diverse within and across components of the system, including products, production approaches and technologies, enterprises, supply chains, natural capital and related ecosystem services, social and cultural support services; and are characterized by a large number of enterprises with a high degree of functional redundancy.	To what degree is the management action, practice or approach likely to increase opportunities for on-farm economic diversification?
Agro-ecological Integrity	The degree to which ecosystems exhibit integrity is a useful indicator of the degree to which activities can be considered sustainable (Morito, 2002). Generally, ecosystems that exhibit integrity have high levels of functional diversity and are biologically productive and resilient, making them capable of self-organization after disturbance. Sustainable agro-ecosystems are agriculturally-mediated systems that are characteristically less diverse and resilient than similar natural ecosystems, but that provide the required ecological goods and services to maintain the productive capacity for agricultural purposes.	To what degree is the management action, practice or approach likely to maintain or increase the capacity of the system to organize and self-correct itself to a state that maintains all of its original functions?

Criteria	Description	Rating Question
Adaptive capacity	Adaptive capacity is considered a key need of farmers for successfully dealing with emerging drivers affecting the sustainability of agricultural production systems (Darnhofer et al., 2010a). Farm systems with high levels of adaptive capacity are characterized by conditions that facilitate self-experimentation and learning; are able to flexibly change daily or weekly work schedules to respond to changing conditions as well as change/revise farm enterprises; and maintain high levels of diversity in terms of farm enterprises, management systems/ approaches, input types and sources, markets for products, and competencies.	To what degree can the management action, practice or approach increase the capacity of farmers to adapt to new challenges and opportunities?

Operational Criteria

Criteria	Description	Rating Question
Technical Feasibility	Some strategies may be promising in theory but impracticable. The feasibility of actions, practices and approaches may be limited by the capacity of agricultural producers to comprehend or prepare for predicted changes, depend on tools that have not been sufficiently developed or diffused, or only work in limited environmental and/or social contexts. In these instances, technical feasibility is limited by adaptability. In instances where feasibility is difficult to evaluate, a risk-based approach can help with decision-making in face of this uncertainty.	To what degree can the management action, practice or approach be adopted by most farmers, based on current knowledge?
Adoptability	According to McKenzie-Mohr and Smith (1999), the likelihood of adoption of any change in behaviour depends on the ability of producers to understand the behaviour and its benefits, perceptions about potential difficulties in adopting the behaviour (such as time required to implement the change, costs associated with implementing the change, side-effects associated with the change), and perceptions about whether the benefits are sufficient to justify the change (McKenzie-Mohr and Smith, 1999).	How likely is it that the management action, practice or approach will be adopted by most farmers?

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. Thus, profitability can be increased by either producing more of something that is marginally profitable (i.e. increasing yield), reducing the cost per unit of production, or by increasing revenue for each unit produced (i.e. product prices). Major operating costs in prairie cropping systems include purchased inputs (fertilizers and pesticides), seed, fuel and labour; thus any reduction in inputs while maintaining yield and quality is beneficial.

        In western Canada, heavy reliance on export markets of agricultural commodities relegates farmers to the role of "price-takers". Developing protectable advantages (where products, processes, knowledge, relationships and/or conditions are both profitable and difficult for rivals to imitate) offers an opportunity to secure profitable market positions over the long term (Porter, 1996). For instance, premiums are available for crops with specific qualities (e.g. high-protein wheat (*Triticum aestivum* L.)) or produced in a specific way (e.g. organic products). When such "higher value" products and the way they are produced are difficult for others to imitate (e.g., the combination of favourable local growing conditions matched with tacit knowledge of organic production techniques for those conditions), the market opportunity is relatively secure and stable. Direct marketing of specialized products to niche markets is also on the rise, even for field-scale products, and can represent opportunities for protectable advantages. Fred Kirschenmann (undated) has suggested that mid-sized farms are well situated to take advantage of larger specialized markets such as the food services industry but currently lack the value chain to connect them to these markets.

        Along with year-to-year profitability, other economic components such as risk management and income stability over years also become important for the long-term economic success of farms (Table 1). The role of support programs through crop insurance, payment for ecological goods and services, and government risk management programs or subsidies are also important to consider.

Resilience

        Resilience refers to the amount of change a system can undergo 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 resilience in both ecological and social realms, as they contribute to the ability of the system to either persist or adapt in the face of stresses and shocks.

        A key aspect of resilience not typically included in other sustainability measures is the tension between adaptability and efficiency (Darnhofer, 2010). While ecological intensification strives to increase productivity through biological regulation, a focus on resilience may require sacrifice of some productivity through maintenance of what appears to be sub-functional diversity. This concept has been illustrated in recent research in a managed oak (*Quercus* spp.)-savannah ecosystem on Vancouver Island in which a highly productive but species-poor mixture of introduced grasses was compared to localized areas with a great diversity of native species with lower productivity (MacDougall et al., 2013). When a major shock was introduced to the system through burning, the species-poor areas were colonized with undesirable woody vegetation within one year, whereas the areas characterized by a diversity of native plants were

re-colonized by over 30 pre-existent grassland species. Thus, important aspects of diversity for resilience include an emphasis on locally adapted species and both functional diversity and redundancy among species.

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. (2010) 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. Kirschenmann (undated) argues that mid-sized farms have more flexibility than large ones and are more likely to be able to adapt to change.

Important indicators of resilience in agricultural systems include the ability to adapt to climate extremes, reduced dependence on external inputs such as non-renewable energy sources, enterprise diversity, agro-ecosystem integrity and the adaptive capacity 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 (Kremen and Miles, 2012). These practices range from relatively simple to highly complex but have the common goal of adding variability in agroecosystem structure and function in areas such as resource use and resistance to pests. This planned diversity attracts additional natural biodiversity, further enhancing ecological integrity (Altieri and Nicholls, 2008).

Crop Varieties and Genetic Diversity

Variety selection

The simplest approach to adding diversity on many farms is to change crop variety. Variety selection receives a great deal of attention in the popular media, with selection criteria based mainly on adaptation to local soil and climatic conditions, yield, ease of management, disease resistance, and end-use quality parameters. While these factors may result in certain increases in farm profitability, variety selection based on these criteria has only a small impact on the sustainability and resiliency of cropping systems. Nonetheless, variety selection is very easy to implement and thus may play a role in increasing the genetic diversity present in prairie cropping systems. For instance, in an Alberta study, rotation between three barley (*Hordeum vulgare* L.) varieties reduced disease incidence and enhanced barley yield and kernel size compared to growing the same variety every year; however, rotating to a different cereal crop species (triticale (*X Triticosecale*)) provided even greater benefits (Turkington et al., 2005). These authors noted that, while the beneficial effect of cultivar rotation could be important where crop selection options are limited, additional practices to add diversity are also required.

While new varieties continue to be developed every year, interest in heritage or historical varieties has surged in recent years. Cultivars of wheat used before the advent of high-input agriculture (1880-1950) are considered by some organic producers to be better suited than modern cultivars for organic management and, in some cases, are in demand for their baking qualities (e.g. Red Fife). Older cultivars have been shown to be more responsive to mycorrhizal colonization than modern cultivars, which would enhance the cultivar's nutrient acquisition capabilities in lower fertility conditions (Hetrick et al., 1992). The taller growth habit of older cultivars may also allow these cultivars to compete more aggressively with weeds, a major obstacle of organic production. There are few studies that compare the grain yield and harvest index of heritage cultivars versus modern Canada Western Red Spring (CWRS) cultivars and amongst these studies there are inconsistent results (Wang et al., 2002).

Pridham et al. (2007) investigated the responses in weed populations, biomass, disease levels and grain yields of heritage and modern cultivars and cultivar mixtures under organic management. Some results were surprising. For example, at one site, the most recently developed cultivar, 5602HR, experienced the most weed problems yet produced the highest grain

yield. This observation suggests that modern cultivars can yield well under organic production but may increase future weed problems. On the other hand, the two modern cultivars tested seemed to offer no significant advantage in lowering the foliar leaf disease severity compared with Red Fife, a cultivar that was developed a century ago. In fact, the two most severely disease affected cultivars were the modern cultivar, AC Barrie, and the heritage cultivar, Marquis. This preliminary research also demonstrated that Red Fife, a heritage cultivar, was capable of producing yields comparable to modern cultivars.

The role of crop breeding environment on the characteristics of the resulting variety has come into question as organic and low-input farmers look for varieties that are well suited to the growing conditions on their farms. Breeders in both Manitoba and Alberta have found that spring wheat 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).

Awareness of the poor suitability of some modern varieties to ecologically-based cropping systems has fostered interest in unconventional crop breeding strategies. For example, horizontal or quantitative breeding for disease resistance, participatory plant breeding projects, and use of landraces are seen as useful tools for developing varieties that are resilient and locally adapted (Robinson, 2007; Newton et al., 2011).

Cultivar mixtures

Growing more than one cultivar of a particular crop in a field at the same time may be an option for increasing genetic diversity without a large increase in crop management complexity. Crop cultivar mixtures involve crop cultivars that are comparable agronomically, but may be phenotypically dissimilar (Mundt, 2002). Recent research has shown that intraspecific genetic diversity may play a larger role in ecological interactions than previously thought (Cook-Patton et al., 2011). Cook-Patton et al. (2011) found that increasing diversity through variety mixtures resulted in the same level of increase in primary plant productivity as through species mixtures; however, variety mixtures did not increase arthropod diversity as much as species mixtures.

Cultivar mixtures have been used successfully to reduce yield losses from leaf disease in spring barley crops in the former German Democratic Republic, Poland, Denmark and Switzerland as well as in spring wheat crops in the USA and Germany (Manthey and Fehrmann, 1993; Newton, 1997), while others have found no benefit to blending cultivars (Dai et al., 2012). A meta-analysis of studies reporting on the effect of spring wheat cultivar mixtures studies on stripe rust suggested that cultivar mixtures had lower disease incidence in 83% of cases, with an average disease incidence reduction of 28% (Huang et al., 2012). The maintenance of grain yield and quality as demonstrated by cultivar mixtures is primarily a result of the disease suppression elicited by genetically diverse cultivars in the mixtures (Mundt, 2002). Mixing resistant and susceptible cultivars may also be used as a strategy to slow or avoid the breakdown of disease resistance in crops such as field pea (*Pisum sativum* L.; Bing et al., 2011). On the other hand, 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).

Although disease control by cultivar mixtures is the primary enabler of yield maintenance, higher yield of mixtures over monoculture can also be attributed to competition and compensation between the cultivars in the mixture (Finckh and Mundt, 1992). Complementary use of resources and divergent niches may also play a role in higher yields for

cultivar mixtures (Gallandt et al., 2001). Further, cultivar mixtures may suppress weeds because of morphological differences in cultivars that result in increased competition within the mixture.

In a study on cultivar mixtures in organic production in Manitoba, there was no evidence to suggest that wheat cultivar mixtures resulted in higher grain yields than well-adapted wheat cultivars grown in monoculture (Pridham et al., 2007). However, lower yielding cultivars grown in mixture sometimes yielded as well as the highest yielding cultivar grown alone. Other workers have reported increased yield stability over a range of environments in cultivar mixtures (Mengistu et al., 2010). Thus, cultivar mixtures may provide a certain level of yield and income stability. 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 within a cropping system may have a relatively large effect on sustainability, profitability and resilience. 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, choosing crops that are more flooding tolerant (e.g. soybean (*Glycine max* (L.) Merr.) instead of other grain legumes; oats instead of wheat; sunflower (*Helianthus annuus* L.) instead of corn (*Zea mays* L.) increases crop resilience to excess water conditions. Further, some crops are better than others in terms of enhancing soil health. For example, oats are better for soil building than wheat and wheat provides more residual C to the soil than lentils. On the other hand, lentils are more mycorrhizal than wheat resulting in better soil aggregation potential.

When crop selection is extended over temporal and spatial scales, a substantial level of diversity can be incorporated into an annual cropping system. 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., 1998; Campbell et al., 2011; Davis et al., 2012).

Highly effective crop rotations include high levels of functional diversity, not just a large number of different crop species. Including crops that vary in their water use, nutrient use, crop life cycle (i.e. spring vs. winter cereals), photosynthetic pathway (i.e. C3 vs. C4), potential for mycorrhizal colonization, and tillage regime can add a degree of functional diversity to crop rotations that is far beyond the level achieved with several species of similar crops.

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 greenhouse gas (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 and the accompanying reduction in N fertilizer requirements (Asgedom and Kebreab, 2011).

Cover Crops

A cover crop is 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 biological N

fixation, weed or pest suppression, prevention of soil erosion or others. As such, cover crops have considerable potential to increase the environmental sustainability of cropping systems.

Choosing a cover crop species and a method for including it in the cropping system require careful examination of the spatial and temporal niches available in a cropping system (Snapp et al., 2005). Where cover crops are commonly used is in temporal niches, where cropland would otherwise be left fallow (e.g. winter cover crops in the Northern USA, summer cover crops in the southern USA; Snapp et al., 2005). The short growing season of the Canadian prairies limits the temporal niches available for cover crops, creating challenges for cover cropping systems for this region. Nonetheless, opportunities do exist to integrate cover crops into prairie cropping systems, using both temporal and spatial niches.

Interseeding and relay crop systems for cover crops

Growing an understory crop or cover crop together with a cash crop is one way to fill a spatial niche in an annual cropping system. The goal of this type of intercropping is to maintain or increase the yield of the main crop, while realizing other benefits from the secondary crop, such as post-harvest soil cover, N fixation for subsequent crops (if a legume is used) and weed suppression. This system may be referred to as interseeding or underseeding, or relay cropping if the establishment of main and secondary crops is staggered. 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 northern USA (e.g. Bruulsema and Christie, 1987; 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. For example, cover crop systems have been investigated using spring-seeded mixtures of cash and cover crops in the northern US, using berseem clover (*Trifolium alexandrinum* L.) and annual medics (*Medicago* spp.) as the interseeded crop, and in Manitoba, using red clover (*Trifolium pratense* L.) and hairy vetch (*Vicia villosa* Roth; Moynihan et al., 1996; Sheaffer et al., 2001, 2002; Pridham and Entz, 2008). In general, these interseeded legumes added N to the system, had variable effects on weed biomass, and increased the yield of the following crop in some cases. Interseeding a cover crop together with a cash crop reduced yield of the cash crop in some cases and maintained or increased it in others, 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, in which seeding of cash and cover crops is staggered, may offer more control over resource competition between the cash crop and the cover crop. The goal of these systems is to establish a cover crop under the canopy of the cash crop so that the cover crop is poised to take advantage of available resources immediately after cash crop harvest. According to an analysis of available late-season heat and moisture resources in the Canadian prairies, many locations across the southern prairies receive enough growing degree days after winter wheat harvest to produce a green manure crop; however, southern Manitoba may be the only region that consistently receives enough late-season moisture (Thiessen Martens and Entz, 2001). Even so, in regions receiving less consistent late-season precipitation, late season cover crops could be used on an opportunistic basis. Some climate change scenarios call for warmer and wetter conditions in many parts of the Canadian prairies, which may open up greater opportunities for cover crop use.

Researchers in Manitoba have been investigating relay cropped legumes for more than a decade (Thiessen Martens et al., 2001, 2005; Entz et al., unpublished data) and similar work has

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been done more recently under semi-arid conditions in Alberta (Blackshaw et al., 2010). In both these studies, red clover and alfalfa (*Medicago sativa* L.) were successfully established as spring-seeded relay crops in winter cereals. The AB study also looked at winter pea (*Pisum sativum* L.) and considered both fall and spring legume establishment dates. In Manitoba, red clover and alfalfa relay crops at two locations produced an average of 600-1800 and 190-1193 kg ha^{-1} of biomass, respectively, without reducing grain yield of the main crop (Thiessen Martens et al., 2001). Where soil moisture was not limiting, relay cropped red clover and alfalfa provided fertilizer replacement values of 24-26 and 51-62 kg N ha^{-1}, respectively, to a subsequent oat crop (Thiessen Martens et al., 2005); no significant benefit to the following crop was observed at the dryer of the two sites due to lower cover crop biomass production (Thiessen Martens et al., 2005). Blackshaw et al. (2010) observed red clover, alfalfa and winter pea biomass production of 20-1420, 50-2460, and 1080-4280 kg ha^{-1}, respectively, when interseeded with winter wheat. These researchers reported better legume growth with fall legume establishment than spring establishment and found that fall-seeded legumes increased the yield and oil concentration of a subsequent unfertilized canola (*Brassica napus* L.) crop. In both of these studies, relay cropped alfalfa provided greater benefits to the system than did red clover. Blackshaw et al. (2010) also observed weed suppression by the alfalfa cover crop.

Late-season cover crops, including both interseeded and relay crops, can also have considerable impacts on soil moisture and microclimate. Thiessen Martens et al. (2001) reported 54 mm less water in the soil profile to 110 cm in a relay cropped system than in a sole winter wheat system at Winnipeg (wet climate with heavy clay soil), but a much smaller effect at Carman (dry climate with light-textured soil); air temperature moderation by red clover near the soil surface was also observed in this study. Blackshaw et al. (2010) observed lower available soil moisture the following spring only in the fall-planted alfalfa relay crop system in Alberta. In a berseem clover cover crop interseeded with oat in Manitoba, late-summer soil moisture was 35% lower where the cover crop was grown, but soil temperature moderation resulted in a shallower depth of freezing and, consequently, early spring thaw and greater snowmelt infiltration (Kahimba et al., 2008). Soil water depletion by the cover crop can be a detriment in dry climates and a benefit in wet climates.

Another adaptation of the legume interseeding system that allows for its use in shorter growing season regions is to harvest the main crop as forage. Berseem clover can be intercropped successfully with various forage cereals, including barley, oat and triticale (Ross et al., 2004). In this Alberta study, cereal-berseem clover intercrops produced an average of 12.5 Mg ha^{-1} of total growing season biomass, with few differences in total biomass production between cereal crops. While triticale and oat tended to produce greater first cut yields (i.e. at milk or soft dough stage of cereal), regrowth of berseem clover after cereal forage removal (second cut) tended to be higher after barley than after the other cereals. In a parallel study, cutting dates of oat-berseem clover intercrops affected forage quality parameters but not total biomass yield, suggesting that this system could provide producers with flexibility of forage harvest (Ross et al., 2005).

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.

One of the main challenges in double crop systems in the Canadian prairies is establishment of the second crop during a part of the growing season that receives extremely variable precipitation (Thiessen Martens and Entz, 2001). Researchers in southern Manitoba have successfully established double crops after fall rye (*Secale cereale* L.) or winter wheat over several years of research (1998, 1999, 2006 – 2010). However, biomass produced by these crops has been extremely variable, ranging from 95 to 1936 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; Entz et al., unpublished data).

Harvesting the first crop as forage allows for earlier seeding of and a longer growing season for the second crop. This type of system has recently gained popularity among livestock producers in the northern USA, where cover crops are seeded in late summer after annual forage harvest and grazed in late fall. Researchers at North Dakota State University found that producing an annual forage cereal prior to the summer-seeded cover crop reduced cover crop biomass production dramatically, especially when the cereal was not sprayed with glyphosate after forage harvest (Fraase et al., 2010). Nevertheless, some double crop systems were found to be more economical than custom feedlot feeding.

Self-regenerating cover crops

A major deterrent to implementing cover cropping systems is the cost and uncertainty of establishing cover crops. For this reason, self-regenerating cover crops, which reseed themselves, may be of interest for Canadian prairie cropping systems. A novel forage-based cropping system has been used successfully for decades in Australia, where self-regenerating subterranean clover (*Trifolium subterraneum* L.) and annual medic are grown in pasture-grain systems (Grace et al., 1995). There has been considerable interest in adapting these systems to the NGP region. Sims and Slinkard (1991) concluded that black medic (*Medicago lupulina* L.) had potential for replacing summerfallow in a wheat-fallow cropping system in Montana. Long-term field trials demonstrated that 'George' black medic (Sims et al., 1985) successfully re-seeded itself and boosted wheat yields by 1300-kg ha^{-1} compared with wheat on summerfallow. While the traditional ley farming system of Australia includes a grazing phase, researchers in the NGP are investigating both grazing-based and stockless systems in fallow-based and continuous grain production systems (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 eight years 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, 1998). Late season heat and water resources in the southeastern prairies are likely sufficient to allow for biomass and seed production by several annual medic and subclover species in such a system (Thiessen Martens and Entz, 2001).

Annual medics can regenerate successfully from the seedbank in the NGP (Carr et al., 2005a, b; May et al., 2010; Braul, 2004). Other species such as birdsfoot trefoil (*Lotus corniculatus* L.) can also regenerate successfully and produce adequate quantities of biomass (Carr et al., 2005a, b). Effects of self-regenerating legumes on crop yield vary. Carr et al. (2005b), in western 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. May et al. (2010), in south-eastern Saskatchewan, 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 reduced to 20% of the recommended rate, suggesting that medics may

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provide the most benefit in organic and low-input crop production systems. A yield increase of this size, with low input costs, would represent a substantial increase in the profitability of the system.

Even for promising self-regenerating legumes, dry matter or forage production of these crops when included in annual cropping systems was extremely variable, ranging from 27-3100 kg ha^{-1} at Indianhead (May et al., 2010) and from less than 500 to over 3000 kg ha^{-1} in North Dakota (Carr et al., 2005b). Available soil moisture appeared to be the main factor affecting biomass production in both studies. Forage quality characteristics were determined to be equal or superior to those of alfalfa and red clover (Carr et al., 2005a). While forage production by the legume may be a benefit to the system, grazing livestock may in turn provide a benefit to the self-seeding crop: Carr et al. (2005b) suggested that grazing ruminant livestock could promote increased legume reseeding by removing crop residue while simultaneously burying legume seeds through hoof action.

Screening of self-regenerating legumes for local adaptation has occurred at several locations within the NGP, including central Manitoba, Wyoming and Minnesota (De Haan et al., 2002; Walsh et al., 2001; Entz et al., 2007). While these studies failed to identify a particular species or genotype that would satisfy all the requirements of a self-regenerating cover crop system, they all 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. For instance, fall rye 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). A killed mulch system for field scale cropping has been developed in Brazilian no-till systems using a crimper-roller to desiccate a mulch crop grown in-situ. This system is also under investigation in various locations in North America (e.g. Mischler et al., 2010; Vaisman et al., 2011). Killed fall rye mulches may also offer an opportunity for weed suppression in organic and low-input soybean and edible bean systems (Davis, 2010).

Green manures/annual forages

In regions where limited heat and/or moisture resources are available, the benefits of cover crops may also be realized by producing spring-seeded annual forages or green manure crops. Many cereal and legume species as well as mixtures have good potential for biomass production and thus soil protection, weed suppression and contribution of organic matter to the soil. Annual legumes offer the additional benefit of N fixation, which is discussed in more detail under Endogenous Input Systems below. Along with these biomass-related benefits, 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} (McCartney and Fraser, 2010; Bullied et al., 2002; 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., 1998; Carr et al., 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 while recognition of the benefits of annual legumes is growing, it remains challenging to find a niche for these crops. The main barrier to adoption of annual green manure and forage crops may be economic: green manure crops require taking a year out of cash crop production for grain farmers and high seed and establishment costs make annual forages more expensive than perennial forages for livestock producers.

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). While some information exists on the productivity and forage quality of annual green manures and forages, very little research has been published on grazing these crops in the NGP region (McCartney et al., 2009; McCartney and Fraser, 2010). Recent grazed green manure experiments in Manitoba suggest that annual legume green manures can be grazed while maintaining the yield of the following crops (Harun Cicek, personal communication, Jan 2013). This promising practice is discussed further under Crop-Livestock Integration below.

Annual Polyculture

Grain intercropping, or polyculture, is another approach to increasing diversity within annual cropping systems. Grain intercrops are those that include more than one crop harvested for seed. While it is generally accepted that the yield of each component crop will likely be reduced, intercrops are thought to offer benefits such as overyielding (increased total yield compared to monocultures), increased resource use efficiency, weed suppression and yield stability (Liebman and Dyck, 1993; Jensen, 1996; Szumigalski and van Acker, 2005).

There is limited documented research work on grain intercropping in the Northern Great Plains and the results of this research are inconsistent. Overyielding and increased yield stability have been observed by Szumigalski and van Acker (2005) in some combinations of wheat, pea and canola in Manitoba, most consistently in canola-pea and wheat-canola-pea intercrops. Other researchers have observed little or inconsistent yield benefits from intercropping. In an Alberta study, Hummel et al. (2009) reported canola-wheat intercrop yields that were similar to those of monocrops. Carr et al. (1995), working in North Dakota, found that intercropping wheat and lentil had little effect on wheat yield but reduced lentil yield dramatically, and had little effect on land equivalency ratios. In a more recent study, Carr et al. (2004) observed higher total above-ground plant biomass production for barley-pea intercrops in low N soils; no benefit of pea in the barley crop was observed under high soil N conditions. In a Manitoba study under organic management, intercropping spring wheat with various other crops had variable yield results (Pridham and Entz, 2008).

The success of a particular intercrop depends on a variety of factors, including the competitive ability of component crops, component ratios and seeding rates, nutrient availability and weed pressure. For instance, specific intercrop mixtures may perform differently under organic vs. conventional management (Kaut et al., 2008) and the yield advantage of intercrops

may increase as the number of component crops increases (Nelson et al., 2012). Intercrops that include mixtures of competitive and uncompetitive crops tend to yield better than the monocrop yield of the uncompetitive crop but less than the monocrop yield of the competitive crop (Pridham and Entz, 2008; Nelson et al., 2012). This relationship may be used to economic advantage when the noncompetitive crop has a high value (Pridham and Entz, 2008).

In spite of a lack of clear evidence for increased yield, many of these studies reported other benefits observed in grain intercrops. Weed suppression was observed by Szumigalski and van Acker (2005) and Carr et al. (1995), who attributed this effect to enhanced canopy development by the intercrop. Pridham and Entz (2008) and Nelson et al. (2012) also reported lower weed densities and weed biomass in certain cases. Lower levels of plant disease have been observed in wheat-pea, wheat-canola, wheat-rye, oat-barley, barley-pea, barley-faba bean (*Vicia faba* L.), and barley-lupin (*Lupinus* spp.) intercrops (Vilich-Meller, 1992; Jensen et al., 2005; Pridham and Entz, 2008; Hummel et al., 2009). Szumigalski and van Acker (2006) observed other potentially beneficial processes in intercropping systems, such as N sparing, greater crop N concentrations, and more efficient use of land area for protein production, as well as possibly mitigating the potential for nitrate leaching following field pea production. Hummel et al. (2009) reported increased canola oil content and wheat protein levels in wheat-canola intercrops in some cases. 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).

While results from research on intercropping in the NGP region are inconsistent, the occurrence of potential benefits in certain cases suggests that this is a practice that deserves further research to develop successful intercropping systems for this region, especially in light of the prevalence of successful intercropping systems in farming systems worldwide. Designing successful intercrop combinations and management practices requires testing of the almost infinite possibilities under various soil and weather conditions. For instance, adjusting seeding rates of crop components may have a major impact on the success of the intercrop and is easy to implement. Some prairie farmers have already developed highly successful grain intercropping systems (Colin Rosengren, personal communication).

The benefits of intercropping may also be realized in non-grain crops such as cover crops, green manures, and annual forages. In these crops, polycultures do not present the disadvantage of complexity of harvest, and so create a more accessible opportunity to take advantage of the benefits of intercropping. Cover crop mixtures have been observed to be more productive than individual cover crop species grown alone (Wortman et al., 2012). In addition, 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 and efficient resource use. Perennials are known to increase C storage in soils and have the potential to reduce GHG emissions (Pretty, 2008; Asgedom and Kebreab, 2011). While forages are the most common perennial crop in the Canadian prairies, other opportunities to incorporate perennials into our cropping systems already exist and more are being developed.

Perennial forages

Perennial forage crops are common in Canadian prairie cropping systems, especially in cattle-producing regions where seeded forage crops supplement native rangelands. Rotating perennial forages with annual crops occurs on 5-15% of arable land in the region (Entz et al., 2002).

The benefits of perennial forages in rotation are well documented and have been summarized by Entz et al. (2002) and 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 eight years after forage termination (Hoyt, 1990). Farmers have also observed yield increases due to forages in rotation, with 71% reporting enhanced grain yields after forages compared to annual crop rotations in a survey of Manitoba and Saskatchewan forage producers (Entz et al., 1995).

Perennial forages, especially legumes, can have a major impact of 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 years) 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 where biomass is removed. In these systems, phosphorus (P) depletion can occur within a relatively short time frame, especially under organic management where synthetic fertilizers are not used (Welsh et al., 2009). Returning livestock manure to the system can close the nutrient cycle and prevent depletion of soil nutrients. Harvesting forage by grazing instead of haying would effectively cycle most of the nutrients within the system, without the cost of removing hay and applying manure.

The effects of perennial forages on other rotation crops also include non-N factors. Perennial forages also 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). Conversely, 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 (Entz et al., 2002; Arnold et al., 2007).

Economic benefits of including perennial forages in rotation can include lower input costs and reduced income variability, along with enhanced crop yields as discussed above (Entz et al., 2002). The lifespan 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 because 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 greenhouse gas emissions and providing wildlife habitat (Pimentel et al., 2012).

Researchers at the Land Institute in Salina, 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). So far, the main crop of focus has been wheat, with efforts also being devoted to sorghum (*Sorghum* spp.), sunflower, rice (*Oryza* spp.), rye, maize, and others (Pimentel et al., 2012). Recent evaluations of perennial cereal lines in Australia and the US 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). In a Michigan evaluation of 4 perennial wheat accessions and one perennial rye accession, perennial wheat and rye grain yields were about 50% and 73%, respectively, of annual grain yields and were similar between 1 year old and 2 year old plants (Jaikumar et al., 2012). It is interesting to note, however, that this study was terminated after the second year due to poor regrowth, which was attributed to unusually hot, dry conditions (Jaikumar et al., 2012). Evaluation of 176 wheat × wheatgrass (*Thinopyrum* spp.) derivatives in Australia identified a number of lines that produced three successive grain crops (Hayes 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). However, continued breeding efforts are expected to narrow these gaps. In addition, these lower yields may be offset economically by reduced input costs. For instance, fertilizer and pesticide requirements are expected to be lower due to better resource use efficiency and pest resistance in perennial grains. In an economic analysis of perennial grain systems in Australia, Bell et al. (2008) suggested that perennial wheat would need to yield 65% of annual wheat to make it economically feasible; however, if dual-purpose perennial wheat was grown, providing forage for grazing livestock, the grain yield requirement of the perennial wheat would drop to 40% of annual wheat. Key aspects of the economic viability of perennial grain systems appear to be the dual-purpose nature of the crop, allowing for grain harvest as well as grazing, and the ability of the system to function with very low or no inputs of pesticides and fertilizers (Bell et al., 2008; Pimentel et al., 2012).

Perennial grain research in Manitoba currently includes a plant improvement program for intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth & D.R.Dewey) and a domestication program for perennial sunflower (*Helianthus maximilliani* Schrad; Doug Cattani, personal communication, Feb 2013). The focus of the intermediate wheatgrass program is to select for winter survival, seed yield and quality, and stable productivity over several years. Intermediate wheatgrass may be treated as a dual-purpose crop, possessing high straw quality and offering grazing after seed harvest. While this crop may not have the baking qualities of annual wheat, it has excellent potential as a specialty flour, and could become commercially available in approximately 15 years. Agronomic trials investigating nutrient management and post-harvest renovation of intermediate wheatgrass will begin in 2013. The sunflower domestication program is currently characterizing the seed size and flowering synchronicity traits of native Manitoba sunflowers to select plants for future crosses.

Various approaches have been presented for management of perennial grain crops. Some suggest the ideal system would be a permanent perennial polyculture of grasses, legumes and

composites, mimicking a native prairie ecosystem (Piper, 1998). In such systems, complementary resource use and N-fixation by legumes can result in greater yields than in perennial monocultures (Piper, 1998; Weik et al., 2002) and community diversity would mitigate major pest and disease outbreaks (Cox et al., 2005). However, poor synchronicity of seed maturity may pose challenges for grain harvest (Weik et al., 2002). Others propose 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). These systems require ease of establishment and relatively high yield before they would be considered more advantageous than annual crops (Bell et al., 2010).

While it may be many years before high-yielding perennial grains become commercially available, there is potential to use some intermediate products. For instance, although early lines of perennial cereals do not possess acceptable milling qualities, they could be used primarily for grazing with opportunistic grain harvest, or the grain could be used as animal feed (Bell et al., 2010; Hayes et al., 2012; Doug Cattani, personal communication, Feb 2013).

Perennial polycultures
The benefits of polyculture observed in annual crops are also attainable in perennial crops. In fact, perennial forages are commonly grown in polyculture to provide a balanced nutritional profile and create yield stability under varying weather conditions. Studies in Iowa and Virginia comparing productivity of perennial prairie mixtures to monocultures of these plants corroborate the positive effect of diversity on productivity (Picasso et al., 2011; Bonin and Tracy, 2012). In these studies, overyielding by mixtures was greatest and most consistent in more diverse mixtures (4 or more species) and increased over the years of the study. 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 (Sturludóttir 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 are those that deliberately integrate woody plants (trees, shrubs) into agricultural production systems (Lassoie and Buck, 2000). There are several approaches to incorporating permanent woody vegetation into grain cropping systems, including ecological buffer strips, alley cropping systems and silvopastoral systems. Under this broad definition, even the practice of planting field shelterbelts can be considered an agroforestry practice. Agroforestry systems vary widely in their purpose for establishment and in the physical arrangement of crop and tree areas, but all agroforestry systems can potentially contribute to the environmental sustainability and resilience of prairie cropping systems along with, in some cases, providing harvestable products that enhance system profitability.

Adding woody plants (shrubs and/or trees) to cropping systems through agroforestry adds yet another layer of biological and functional diversity to the system. Generally speaking, 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; soil conservation and regulation of soil organic matter. Many of these benefits are attributed to increases in planned biodiversity (e.g. adding trees and shrubs to annual cropping systems), which generally results in subsequent increases in associated biodiversity (e.g. attracting wild pollinators by creating suitable habitat; Altieri and Nicholls, 2008).

Shelterbelts and ecobuffers

Shelterbelts or windbreaks have been 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 is generally for soil conservation and snow capture, both of which are related to reducing wind speed. A shelterbelt with optimal porosity (30%) may 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, 1998; 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).

In the Canadian prairies, where 20-40% of annual precipitation falls as snow and 15-40% of this moisture may be lost through sublimation during snow transport by wind (Pomeroy and Gray, 1995), snow capture on fields adjacent to shelterbelts may result in considerable moisture conservation. Kort et al. (2012) reported a 29% (approximately 9 mm) increase in snow water equivalent in sheltered fields over unsheltered ones, and determined through modeling that shelterbelts spaced at intervals of less than 200 m are likely most effective at reducing loss of moisture through sublimation. Highly porous shelterbelts, such as single rows of trees, prevent development of large drifts and thus result in best distribution of snow across the field (Scholten, 1988, CAESA, 1994).

Reduction of wind speed during summer months may also reduce evaporative losses and microclimate effects (increased temperature and humidity) may increase water use efficiency of crops (Zink, 2010).

Shelterbelts have also been associated with benefits such as increased soil organic C, reduced bulk density, improved air and water quality, enhanced biodiversity including associated recreational activities such as bird-watching, reduced pesticide drift, and improved aesthetics (de Jong and Kowalchuck, 1995; Kulshreshtha and Kort, 2009).

Recent work in western Canada is seeking to expand the role of shelterbelts beyond microclimate modification to include direct enhancement of ecological services. These multifunctional shelterbelts, or "ecobuffers", are densely planted strips of a diverse mix of native tree and shrub species that establish quickly and create a biologically diverse area within a farm landscape (Schroeder et al., 2011). They are designed to provide specific ecological services such as wildlife habitat, improved pollination, nutrient cycling, pest suppression, C sequestration and/or production of food, fuel, timber, etc. While shelterbelts have also been observed to provide some of these services, designing ecobuffers with specific services in mind will likely enhance the delivery of these services.

Agroforestry-grain systems or tree-based intercropping

While shelterbelts are common on the Canadian prairies, more intensive agroforestry systems that integrate trees and shrubs more fully into crop production systems are less so. Little work has been done in the Northern Great Plains region, but results from other temperate areas suggest that these systems have the potential to be feasible and environmentally beneficial in the Canadian prairies.

Many agroforestry systems used around the world are also called tree-based intercropping systems or alley cropping systems, and typically include trees planted in widely spaced rows with agricultural crops grown in the alleys between the rows. The tree component of the system may be established for varying purposes, including fruit or nut production (e.g. walnut (*Juglans* spp.)), timber production (e.g. walnut, maple (*Acer* spp.)), bio-energy production (e.g. willow (*Salix* spp.), hybrid poplar (*Populus* spp.), or as a type of perennial green manure (various N-fixing trees or shrubs) where trees prunings are applied to the crops in the alleys. Agroforestry research in Canada has typically focused on bio-energy and timber species of trees, mainly hybrid poplar so far; however, considerable potential exists to include other types of trees in agroforestry systems on the prairies. For instance, fruit trees and shrubs such as saskatoon berries (*Amelanchier alnifolia* Nutt.), sea buckthorn (*Hippophae rhamnoides* L.), and hardy sour cherries (*Prunus cerasus* L.) are being successfully grown on the prairies and could be more fully integrated into agroforestry systems.

The environmental and ecological services of trees in agroforestry systems, also called tree-based intercropping or alley cropping, are well documented and have been the focus of several studies in central Canada (Ontario and Quebec). Beneficial effects observed include increase soil organic C, greater C sequestration (Thevathasan and Gordon, 2004; Peichl et al., 2006; Oelbermann and Voroney, 2010), reduced leaching of water contaminants including nitrate and E. coli (Thevathasan and Gordon, 2004; Dougherty et al., 2009, Bergeron et al., 2011), reduced N_2O emissions (Beaudette et al., 2010), enhancement, diversification and stabilization of arbuscular mycorrhizal fungi 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 5-8 years old. In other regions of North America, researchers have observed other beneficial effects of trees in cropping systems 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).

Tree-based intercropping systems are capable of increasing total productivity, according to a European study in which land equivalency ratios for these systems were consistently greater than 1; however, high productivity levels depended on high soil moisture availability and system designs that optimized complementary resource use (Graves et al., 2007). In examining the potential productivity of such systems, many studies have attempted to characterize the interactions between the tree and grain crop components of the system. Results from these studies vary, suggesting that local conditions (specifically resource availability) and choice, arrangement, and management of tree and crop components will have a major effect on the productivity of the system. Researchers in central Canada have found yields of many cool-season crops such as wheat and canola to be similar in tree-based intercropping and crop monoculture systems (Thevathasan and Gordon, 2004; Beaudette et al., 2010) while C4 crops such as corn tend to suffer yield reductions in agroforestry systems (Thevathasan and Gordon, 2004;

Reynolds et al., 2007). Varying results have been obtained for soybean, a warm-season C3 plant (Thevathasan et al., 2004; Reynolds et al., 2007; Dougherty et al., 2009; Rivest et al., 2009). 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 and that allow component crops to interact in a complementary rather than competitive manner. This should be an area of future research in the Canadian prairies.

While alley cropping systems that use pruning from N-fixing trees or shrubs as a nutrient source are uncommon in North America, there is potential for these systems to replace N fertilizer in small-scale production of high-value crops (Rhoades et al., 1998).

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). An analysis of central Canadian tree-based intercropping systems found that these systems were 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 such as red oak (*Quercus rubra* L.; Toor et al., 2012). These authors suggest that payments in a carbon market or a grant/subsidy program for ecological services would be necessary to encourage adoption of these systems. Conversely, a European study found that many agroforestry systems were economically attractive, especially if high-value tree species were chosen; if trees were included for landscape or ecological purposes, financial support payments would be necessary (Graves et al., 2007).

Reducing Tillage

Tillage is known to be responsible for soil erosion and loss of organic matter, along with negative effects on some soil organisms. Thus, reducing tillage is seen as an important aspect of sustainable farming systems. 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. Adoption rates of no-till are 60, 48 and 21% in Saskatchewan, Alberta, and Manitoba, respectively (Derpsch et al., 2010).

Positive effects of no-till on soil health parameters have been documented around the world 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 Northern Great Plains have reported better soil aggregation as well as higher levels of soil organic C and potentially mineralizable N in no-till soils (McConkey et al., 2003; Liebig et al., 2004; Pikul et al., 2007; Malhi et al., 2009; Lafond et al., 2011). Microbial biomass, especially of mycorrhizal fungi, is often greater in no-till soils (Liebig et al., 2004; Helgason et al., 2010); soil organism community structure may also be different in no-till than tilled soils (Helgason et al., 2010). However, in other studies, no effect of tillage on mycorrhizal colonization of crop roots has been observed (Monreal et al., 2011).

Yields of crops under no-till vary, depending on crop species and weather conditions (e.g. Mahli and Lemke, 2007). No-till often, but not always, results in greater crop yields and better

water use efficiency under dry conditions, while yields under no-till can be reduced under wet conditions (Azooz and Arshad, 1998; Arshad et al., 2002). Yields may also be reduced when N is limiting due to a reduced rate of N mineralization under no-till (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 years, and possibly even after 31 years, no-till soils may still be in a soil-building phase. This suggests that agricultural soils under tillage systems are extremely degraded and emphasizes the importance of long-term monitoring of cropping systems changes.

No-till systems may offer an additional contribution to sustainable cropping systems by facilitating the cycling of perennial forages in rotation. Small-seeded perennial forages are typically seeded with a companion crop to enhance forage crop establishment; the companion crop minimizes soil blowing, lowers soil temperatures and provides shading (Allen and Entz, 1994). However, these authors note that these same benefits can be provided to forages in the establishment phase through no-till seeding, without the competition and associated forage yield reduction from the companion crop. No-till seeding increases water availability to germinating forage seeds, compared to conventional seedbed production, resulting in better establishment.

Traditional forage stand termination typically requires several tillage operations; thus alternative termination methods can reduce the tillage required to move from perennial forages into annual cropping sequences. Forage stand termination using herbicides is feasible and can enhance soil water conservation and reduce weed pressure in subsequent crops (Entz et al., 2002 and references therein).

While some equate no-till agriculture with conservation agriculture (e.g. Derpsch et al., 2010), others define conservation agriculture according to a more specific set of principles: minimal soil disturbance, retention of crop residue on the soil surface and diversification of crop rotations through cover crops and/or intercropping (Scopel et al., 2013). Conservation agriculture has had major application in tropical countries, particularly those using non-mechanized farming practices, with major improvements in crop yields and soil health (Derpsch et al., 2010).

No-till in North American has not typically included the same emphasis on crop diversity through intercropping and cover crops. Strengthening this focus in Canadian prairie no-till systems could have major benefits for the productivity, sustainability and resilience of these systems. 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 nutrient recycling within the system, with limited external inputs. In contrast, most cropping systems have become heavily dependent on synthetic fertilizer application for delivery of nutrients to crops. External inputs comprise a large fraction of the energy use and ecological footprint of conventional farming systems (Hoeppner et al., 2006; Bavec et al., 2012). The high energetic and financial cost of fertilizer, especially N, as well as the effects of synthetic fertilizer use on soil organic matter and soil microbial communities (Phelan, 2009) has led many to consider ways of reducing fertilizer use and instead provide crops with the nutrients they require using inputs that originate within the system, also

known as endogenous inputs. In fact, 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." Since agricultural systems, by nature, require export of a certain amount of nutrients, it is unlikely that the entirely closed-loop systems observed in nature can be achieved. However, there is considerable room 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).

Animal Manure and Compost

Use of animal manure as a nutrient source for crops is an age-old practice that has fallen out of favour with the separation of crop and livestock production systems and the availability of easy-to-use synthetic fertilizers. This has resulted in animal manure often being 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 on nutrient supply, as well as soil and crop health, is growing, along with awareness of how to mitigate potential water and air quality issues. The most widely available types of animal manures in the Canadian prairies are cattle, hog, and poultry.

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). While much of the benefit to crops may be through nutrient supply, non-nutrient benefits are also important. For instance, in a moisture-limited growing season in Utah, organic matter additions in the form of composted manure increased the moisture retention capability of soil and thus improved crop yield (Stukenholtz et al., 2002). In Saskatchewan, crops grown in cattle or hog manure-amended soils had better vigour and were less affected by common root rot than in control treatments (de Freitas et al., 2003).

Manure application to farmland may also produce other benefits. For instance, enhanced soil C, microbial biomass, microbial activity, and populations of nematodes and natural enemies of crop pests have been observed in systems that include livestock manure amendments (de Freitas et al., 2003; Hu et al., 2011; Moulin et al., 2011; Snapp et al., 2010; Garratt et al., 2011). Carry-over effects on crop yield and other benefits of both fresh and composted manure to subsequent years are also commonly observed (e.g. Endelman et al., 2010). In fact, Reeve et al. (2012) observed positive effects on crop yield, soil organic C and microbial biomass 16 years after compost application in dryland wheat production in Utah.

Manure application at high rates and/or frequency of application can result in nutrient accumulation in soils and contamination of surface and ground water, and is also associated with greenhouse gas emissions (Stumborg and Schoenau, 2008; Ashjaei et al., 2010; Miller et al.,

2010, 2011, 2012). Appropriate management practices such as those described by Shoenau and Davis (2007) and others can effectively mitigate the potential for nutrient loss and environmental contamination. For instance, nutrient build-up can be prevented by monitoring soil nutrient levels and applying at rates that 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, 2007) 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 livestock manure on cropland. Transporting liquid manure long distances is energy intensive (Wiens et al., 2008) and has prompted research into methods to separate solid and liquid components of liquid manures (e.g. Fangueiro et al., 2012; Xia et al., 2012) and 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. Lague et al., 2006). Composted manure has been observed to provide greater agronomic and soil health benefits than uncomposted manure (Lynch et al., 2005).

Green Manures

Biological N fixation by legumes currently provides about 18% of N inputs in Canadian agriculture (calculated from Janzen et al., 2003). While the availability of inexpensive synthetic N fertilizer and the move to intensive cropping systems have reduced the reliance of agricultural systems on this naturally-occurring nutrient input process, there is considerable potential and, in the context of rising input costs and increased climate variability, need to explore agricultural systems that make optimal use of legumes for biological N fixation.

Legume crops may be included in cropping systems in many ways. 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 also contribute smaller amounts of N to the system. Along with N fixation, green manures in rotation have many beneficial effects such as addition of organic matter, cycling of other nutrients, weed suppression, disruption of pest cycles, and enhancement of soil physical, chemical and biological properties (Fageria, 2007).

Yield of crops following green manure crops depends largely on biomass production (and associated N fixation and subsequent mineralization) of legume green manures. 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, and 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 is an effective way of optimizing 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).

Along with yield benefits, green manures may also provide other benefits to annual cropping systems. A long-term study in Saskatchewan has shown enhancement of many soil biological parameters in green manure systems compared to fallow systems and continuous grain systems, including populations of soil bacteria and fungi, soil microbial biomass N and C, and microbial activity (Biederbeck et al., 2005). A major benefit to the system is the potential reduction of N fertilizer requirements and the associated reduction in energy use (Pretty, 2008).

The economics of green manures in rotation compared to 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 system 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 and using good soil water management practices (Zentner et al., 2004). However, in continuous cropping systems that do not rely on summerfallow for soil moisture recharge, green manure production requires farmers to forfeit a year of cash crop production, negatively affecting the economics of the system. In certified organic systems, market premiums have the potential to offset the costs of including green manures in rotation (Miller et al., 2008).

Obtaining some direct economic value from a green manure crop can also improve the net returns. In fact, in a Montana study, harvesting grain from a winter lentil green manure improved net returns dramatically, even though the yield of the subsequent wheat crop was reduced (Chen et al., 2012). Grazing green manure crops is a practice that could provide this direct economic value in the form of livestock products, while maintaining the N benefit to the following crop (Thiessen Martens and Entz, 2011), and is discussed in more detail under Crop-Livestock Integration below.

Soil Biological Fertility

Among the many soil health measures in use, soil biological fertility is perhaps the most intriguing, since it links a healthy soil with ability to deliver nutrients to plants. Soil biological fertility can be 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.

Farm management practices have a major impact on soil biological fertility. 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; 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). Since populations and diversity of soil organisms are directly affected by the species of plants grown, crop diversity may be one of the most important contributors to soil biological fertility. 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 may be 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). However, P management is one area where successful examples are evident. 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 become evident in a long-term organic-conventional comparison study in southern Manitoba, where "soil test P" (i.e. readily plant-available P) has become significantly lower in organic systems than conventional (Welsh et al., 2009). In these apparently P-deficient organic systems, however, flax grain P concentration was higher than in conventional systems (Welsh, 2007), indicating that organic soils were able to supply adequate levels of P to flax despite the low plant-available P levels in soil. In this study, organic plots also had significantly higher levels of mycorrhizal colonization (Entz et al., 2004; Welsh et al., 2009) and greater spore density and diversity (Welsh, 2007), supporting the hypothesis that soil biological fertility was responsible for the effective nutrient supply to organic flax.

Along with effective nutrient supply, systems that rely on soil biological fertility could also pose a reduced risk of nutrient loss and subsequent contamination of surface and ground waters, since levels of water-soluble nutrients are typically lower than in systems where nutrients are supplied through inputs of synthetic fertilizers or even livestock manure.

Organic Systems

Organic farming is a system that relies heavily, and often exclusively, on endogenous inputs. In Canada and many other countries, organic farming systems are regulated by production standards enforced by third-party inspection and certification systems. While a range of practices is permitted under the Canadian organic production standards, there is a clear emphasis on environmental sustainability and ecological integrity. According to the Canadian Standards Board of Canada, organic agricultural production is defined as "a holistic system designed to optimize the productivity and fitness of diverse communities within the agroecosystem, including soil organisms, plants, livestock and people. The principal goal of organic production is to develop enterprises that are sustainable and harmonious with the environment" (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). Organic crop yields can vary widely, but are often lower than conventional crop yields. For instance, average wheat, oat, barley and flax (*Linum usitatissimum* L.) yields on 14 organic farms in the eastern prairies were 73-78% of the long-term conventional average yields (Entz et al., 2001). Similarly, in organic-conventional comparison field trials, crop yields are often, but not always, lower in organic systems (e.g. Wortman et al., 2012b). These results are in agreement with a recent meta-analysis comparing organic and conventional crop yields around the world in which organic crops yielded, on average, 75% of conventional crops (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; OACC, 2008a, b).

While average yields may be lower in organic farming systems than conventional, organic production systems are often associated with a number of positive effects. 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 (Hoeppner 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 (Stukenholtz, 2002; Letter et al., 2003). In some cases, these effects are positive even when expressed in relation to provisioning services (i.e. crop yield), suggesting that although there may be some trade-offs between productivity and sustainability, these trade-offs are not necessarily prohibitive and could likely be overcome with more advanced ecological knowledge and its application in organic farming systems.

The role of organic inputs in the form of livestock manure or compost appears to be vitally important to the productivity and sustainability of organic systems. For instance, in a long-term comparison of organic (including compost and legumes; no pesticides) and integrated-conventional (synthetic fertilizers and minimal pesticide applications) crop management systems on a course-textured soil in Michigan, the organic systems built up soil C by 54% and reduced N leaching by 50% (Snapp et al., 2010). However, in organic systems without compost or manure inputs, soil C may actually become lower in organic systems than conventional due to lower productivity in organic systems (Bell et al., 2012). Since yield of organic crops is also enhanced by manure/compost additions (Pimentel et al., 2005; Bavec et al., 2012), this practice has great potential to increase both the productivity and sustainability of organic systems and farming systems in general.

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). Miller et al. (2008) compared transition processes from conventional tilled farming to either organic or no-till farming and found both systems to offer equal net economic returns, even when including the required 3-yr period of transition to certified organic production. 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 on one hand and the environmental damage and reliance on external inputs of conventional systems on the other hand. 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. Organic farming systems that have poor productivity tend to deplete soil organic C (Bell et al., 2012; Leifeld, 2012) and are thus both unprofitable and environmentally unsustainable. Whether the converse is

always true does not appear to be well established; however there are some examples that support this. For instance, addition of livestock manure has many beneficial effects on both productivity and sustainability parameters, as discussed above. Similarly, use of green manure crops for N fixation reduces emissions due to reduced or eliminated need for synthetic fertilizers, while also providing organic matter additions and increasing yield of subsequent crops. The enhanced biodiversity commonly observed on organic farms is a good indicator of ecological integrity and system resilience. Furthermore, organic systems have been identified as having excellent potential for mitigation of climate change through reductions in N_2O 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).

Export of agricultural products from organic systems without inputs to replace exported nutrients can result in eventual mining of certain soil nutrients, such as P. While there is considerable potential to enhance cycling of nutrients in organic systems through crop-livestock integration and soil biological fertility, the openness of agricultural nutrient cycles will need to be addressed in order to create systems that are sustainable in the long-term. Because humans are the dominant users of agricultural products, recycling of nutrients contained in human waste would go a long way to closing agricultural nutrient cycles. However, use of human waste as a nutrient source for food production is rarely practiced and is currently prohibited in certified organic systems.

The reliance of organic crop production on tillage for weed control is another area that requires attention. Investigation of organic no-till systems is underway in several regions of North America, with varying results (Mischler et al., 2010; Vaisman et al., 2011; Carr et al., 2012).

Pretty (2008) argues that the poor productivity of organic systems in developed countries is a sign that sustainable intensification of resources (i.e. increased production using a given amount of resources) has not been achieved in these systems so far. Others, such as Halberg (2012), contend that ecological intensification through harnessing of ecological processes offers great potential to improve productivity in organic systems. This will require greater knowledge of these ecological processes, as well as development of well-designed, locally adapted systems to optimize these processes. This is clearly an area that deserves further research.

Integrated Crop-Livestock Systems

Farming systems that include both crops and livestock were developed many millennia ago. However, availability of synthetic nutrients and industrialization of agriculture have resulted in a decoupling of crop and livestock production systems. Many see this as one of the major areas in which modern industrial agriculture is unsustainable (Thomas and Kevan, 1993; Halberg, 2012). Hence, re-integration of crops and livestock has great potential for increasing productivity, sustainability and resilience in agricultural systems and may counteract the negative consequences of highly specialized agriculture (Hendrickson, 2008).

Crop-livestock integration involves more than the production of both crops and livestock on the same farm. Rather, the goal of such systems 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 extend beyond these functions and include

increased income and income stability (Franzluebbers and Stuedemann, 2007; Russelle et al., 2007) as well as the potential to reduce greenhouse gas emissions from both crop and livestock systems (Asgedom and Kebreab, 2011). Crop-livestock integration also plays a supporting role in other beneficial cropping practices as some techniques, such as growing green manures, cover crops and annual and perennial forages, become more financially attractive when livestock products can be gained from the system (Gardner and Faulkner, 1991; Thiessen Martens and Entz, 2011; Chen et al., 2012).

While forage crops and ruminant livestock are commonly integrated in perennial forage based systems, many other possibilities exist. For instance, annual cropping systems also 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. Ecological functions may be enhanced even further when livestock are integrated into more complex systems; there are exciting examples from around the world of crop-livestock systems involving agroforestry and even aquaculture (Entz and Thiessen Martens, 2009). Optimization of crop-livestock systems in the prairie region requires further exploration of the relationships among soil, crops and livestock, including topics such as 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 specific weeds.

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. This allows for acceleration of nutrient cycles, with nutrients available immediately for plant uptake. In addition to being faster, the microbial processes in the rumen that are responsible for this conversion are 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 in order to optimize the use of nutrients.

Integration of crops and livestock can result in semi-closed nutrient cycles. For instance, 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, which often has low plant-availability. Knowledge of nutrient concentrations in feed and manure is important for effective management.

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).

Grazing in Annual Cropping Systems

Swath, bale and crop residue grazing

Interest in alternative winter feeding systems for cattle has sparked considerable work on swath grazing, bale grazing and crop residue grazing systems. These extensive 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, rather than bale-fed in a typical drylot system, can reduce overall costs by reducing forage harvest and manure hauling costs (Volesky et al., 2002; McCartney et al., 2004; Karn et al., 2005). However, costs associated with watering and checking cattle and forage wastage can in some cases reduce the cost-effectiveness of such systems (Nayigihugu et al., 2007).

While the primary purpose of such systems is to reduce feeding costs (D'Souza et al., 1990; McCartney et al., 2004), there is potential to enhance nutrient return to farmland and the performance of subsequent crops. In two Saskatchewan studies, soil N and P concentrations were increased in at least some field locations after bale or swath grazing on annual cropland or Russian wildrye (*Psathryrostachys juncea* (Fisch.) Nevski) pasture; these nutrient increases were associated with enhanced crop productivity in the following year (Jungnitsch et al., 2011; Kelln et al., 2012). In the pasture study, nutrient recovery from field-deposited livestock excreta was significantly greater (27-41% and 17-27% for N and P, respectively) than that from fresh or composted manure applied to cropland (<10% and 4% for N and P, respectively), indicating that nutrient cycling is more efficient in such winter feeding systems (Jungnitsch et al., 2011). However, concentration of cattle at feeding sites, especially in bale grazing systems, can result in uneven distribution of nutrients with nutrient excesses and risk of environmental contamination at some points (Kelln et al., 2012). In fact, spring run-off from the bale grazed treatments in the pasture study described above had elevated levels of both ammonium-N and orthophosphate-P (Smith et al., 2011). Soil nutrient levels after crop residue grazing may be lower and less prone to loss, due to the lower nutrient content of the forage grazed (Kelln et al., 2012).

Both swath and bale grazing systems can be implemented using annual or perennial forages, on either annual cropland or perennial hay or pasture. The key management difference between these systems in relation to nutrient cycling is that in bale grazing, forages can be moved to a desired location, allowing for nutrient transfer within a system. This practice could be used strategically to enhance soil fertility in areas known to be less fertile.

Green manure/cover crop grazing

Integrating grazing livestock into green manure or cover cropping systems has great potential to improve the economics of the system and thus the adoption potential of biological N fixation by legumes in rotation (Gardner and Faulkner, 1991; Sulc and Tracy, 2007; Thiessen Martens and Entz, 2011).

Research in other regions suggests that crops used as annual green manures in the Canadian prairies typically have high forage quality but variable palatability to livestock and tolerance to grazing (Gardner and Faulkner, 1991; Fraser et al., 2004; Marten, 1978; Miller and Hoveland, 1995). Negative effects on animal health associated with legume green manures include the risk of bloat (Gardner and Faulkner, 1991; Hannaway and Larson, 2004), poisoning of cattle and horses by grazing hairy vetch (Johnson et al., 1992; Panciera et al., 1992; McCartney and Fraser, 2010), and poisoning of non-ruminants by grazing chickling vetch (Rao et al., 2005). Grazing cereals may result in prussic acid or nitrate poisoning, winter tetany, and other ailments (McCartney et al., 2008, 2009), as can grazing brassicas (McCartney et al., 2009).

However, animal health risks posed by grazing can generally be minimized through crop cultivar selection and grazing management. There may be some animal health benefits to grazing in annual systems as well, such as the breaking of parasite cycles.

While research into these systems is limited, results indicate that crop yields following grazed green manure systems are equal to those following green manures that were not grazed (Franzluebbers and Stuedemann, 2007; Mr. Harun Cicek, personal communication). 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. Maintenance of the N benefit in grazed green manure systems is likely due to the small proportion of nutrients retained by grazing livestock as well as the conversion of nutrients into more plant-available forms (Thiessen Martens and Entz, 2011). Enhanced nutrient cycling or ecological intensification may also play a role.

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 had no effect on bulk density or soil aggregate stability (Franzluebbers and Stuedemann, 2008b) and increased soil microbial biomass (Franzluebbers and Stuedemann, 2008a).

Thiessen Martens and Entz (2011) estimate that animal live weight gain could be approximately 90-180 kg ha^{-1} from a grazed green manure producing 2500-5000 kg ha^{-1} biomass and that gross revenue from sales of beef or lamb from grazed green manure systems could range from about \$200 to over \$700 ha^{-1}, depending on forage utilization by livestock, livestock species (i.e. cattle vs. sheep) and livestock prices.

Silvopastoral Systems

The interactions of crops and livestock may be enhanced even further when integrated into agroforestry systems. These crop-livestock-tree systems are known as silvopastoral systems. Such systems range from simply grazing in open forests to take advantage of underutilized understorey vegetation to planned arrangements of trees and forages that optimize the productivity of all components. Silvopastoral systems are common in regions where forestry is a major economic activity, such as the south-eastern US. Similar to tree-crop agroforestry systems, inclusion of grazing livestock in forestry systems can improve long-term cash flow in the period before harvestable tree-based products are available (Clason and Sharrow, 2000). Silvopastoral systems also provide ecological benefits such as enhanced biodiversity of arthropods and birds (Mcadam et al., 2007) and C storage in soil (Haile et al., 2010). Cubbage et al. (2012) suggest that active management of silvopastoral systems is a key contributor to their success.

The productivity of silvopastoral systems is influenced by the complex interactions among trees, forages and livestock and can thus be widely variable. Key factors in productivity include resource sharing by trees and forages (i.e. light, moisture, nutrients), nutrient cycling, and microclimate modification (Clason and Sharrow, 2000). For example, in a Missouri study involving annual ryegrass (*Lolium multiflorum* Lam.) and cereal rye forage grown between rows of 6-7 year old hybrid pine (*Pinus* spp.) and black walnut (*Juglans nigra* L.) and grazed by beef heifers, trees reduced forage productivity in some cases but improved it in others (Kallenbach et al., 2006). These authors suggested that productivity improvements were due to protection from weather extremes through microclimate modification. In the same study, forage quality was

frequently higher in the silvopastoral system than in forages grown alone. Even when forage productivity was reduced, beef heifer average daily gain and gain per ha were equal between treatments, possibly due to enhanced forage quality and protection of animals from wind and extreme temperatures in the silvopastoral system. As trees mature and produce more shade, productivity of forages typically declines. However, pruning lower branches to increase light infiltration has been shown to positively affect forage productivity (Devkota et al., 2009).

Livestock can negatively affect tree survival and productivity through physical damage to trees, especially seedlings, or through soil compaction (Bezkorowajnyj et al., 1993; Lehmkulher et al., 1998). On the other hand, nutrient cycling and understorey vegetation management by livestock can be beneficial to trees (Thompson et al., 2000; McEvoy and McAdam, 2008). Preliminary results from a hybrid poplar silvopasture project in the Peace River region of Alberta indicate that only trees under 2 m in height were damaged severely by cattle (Bank et al., 2011). It appears that excluding livestock from trees is necessary until tree leaders are out of reach of livestock, after which short-duration mob grazing can provide benefits that outweigh the negative effects of tree damage (McEvoy and McAdam, 2008). Avoiding grazing within tree stands when soil is wet can reduce the risk of soil compaction (McEvoy and McAdam, 2008).

Farmscaping

Farmscaping is a term developed by ecological entomologist Dr. Robert Bugg referring to the "modification of agricultural settings, including management of cover crops, field margins, hedgerows, windbreaks, and specific vegetation growing along roadsides, catchments, watercourses, and adjoining wildlands" (Bugg et al., 1998). The term farmscaping has come to be associated with the use of specific plants and landscape features to promote populations of beneficial organisms in agricultural systems. In both approaches, 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), as a result of planned biodiversity (Altieri and Nicholls, 2008). However, additional benefits of these permanent landscape features can include other ecosystem processes such as nutrient cycling, soil C sequestration, and soil and water quality protection (Pretty, 2008; Smukler et al., 2010), as well as provisioning services such as fruit or forage production from these landscape features themselves (e.g. Zink, 2010) and increased productivity from surrounding cropland (e.g. Morandin and Winston, 2006). While high levels of both planned and associated biodiversity are ideal, increases in the functional and structural diversity of the farmscape through strategic inclusion of a few species may provide substantial benefits. For instance, in a study examining on-farm biodiversity and ecosystem

function on a California organic farm, Smukler et al. (2010) found that the positive effect of farmscaping on ecosystem function could be attributed mainly to inclusion of a few keys species along with the biophysical characteristics of various on-farm habitats, rather than species richness per se.

There are many opportunities for farmscaping in Canadian prairie farming systems. Permanent riparian buffer zones, field shelterbelts and other agroforestry systems can provide habitat for beneficial organisms along with other ecological benefits, even though this is not their primary purpose. Ecobuffers, as described above, purposefully combine the snowtrapping and wind speed reduction benefits of shelterbelts with creation of wildlife and beneficial insect habitat. Irrigated crop production utilizing centre pivots present a unique opportunity to use unirrigated field corners, which comprise more than 20% of total field area (Zink, 2010). Planting these corners to perennial herbaceous or woody vegetation would dramatically increase landscape diversity and could provide substantial ecological benefits, while also potentially providing provisioning services. While this type of system has been conceptualized by Zink (2010), it has not yet been implemented to our knowledge.

In many cases, the benefits of farmscaping are difficult to quantify in economic terms. However, one example from northern Alberta clearly demonstrates the beneficial effect of uncultivated land on crop productivity (Morandin and Winston, 2006). In this study, abundance of pollinating bees and canola seed set were highly correlated, with both parameters diminishing with the amount of cultivated land in the local landscape. These authors conclude that profitability of continuous canola production could be maximized by leaving approximately 30% of the landscape uncultivated, due to greater yields from better pollination.

An additional aspect of landscape enrichment not typically included in prairie farmscaping is inclusion of wetlands and waterways on farmland. Small, often temporary wetlands (i.e. sloughs, potholes) play a crucial role in providing habitat for waterfowl (Shutler et al., 2000). They are also important for water retention and filtering and enhance the integrity of the water cycle on a local and regional scale (van de Kamp, 1998; Gleason et al., 2011). Water retention on farmland also plays an important role in preventing nutrient escape and the associated eutrophication observed in many bodies of water, including Lake Winnipeg. Protection of existing wetlands and deliberate creation of wetlands in strategic locations on farms could provide a level of resilience to moisture excesses and shortages, while retaining nutrients within agricultural systems.

Integrated Whole Farm Systems

While individual farming practices can make signification contributions to the ecological compatibility of prairie cropping systems, an integrated approach to developing a whole farm system can create synergies among individual practices and enhance the benefits to the system. For example, land use models ranging from use of best management practices (including conservation tillage, appropriate fertilizer rates, and narrow riparian zones) to highly diversified and ecologically integrated farm operations and landscapes (including 5-year crop rotations, intensive grazing, and establishment of ample riparian zones and wetlands) were developed for two watersheds in Minnesota; the authors concluded that the economic, environmental, and social benefits of the ecologically-based, whole farm systems would exceed those of the systems simply using best management practices in less diverse systems (Boody et al., 2005).

An ecological approach to agriculture involves using nature as a model to guide the design and management of sustainable food production systems. Key principles of this approach involve basing agricultural systems on the structures and processes occurring in natural systems and matching these agricultural systems to local conditions (Malézieux, 2012). It also involves treating, to the extent possible, a farm (or perhaps a local community of enterprises) as if it were a closed system, such that, as much as possible, energy, nutrients, and wastes are recycled within the system. Sustainable agricultural systems depend on ecological processes that promote qualities like 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 within locally-affordable means. 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.

Agricultural ecology is important for agriculture because of the potential it holds to increase the profitability of farms while at the same time reducing their environmental footprint and their dependency on external inputs. Ecological agriculture may encompass many or all of the practices already discussed in this paper and, as such, may realize the benefits attributed to these practices. In addition, intensification of ecological farming systems through the careful management of biological processes offers the potential to attain high levels of both food production and ecosystem services (Doré et al., 2011).

Moving to an ecological understanding of farming systems does not preclude the involvement of modern technologies and advances in agricultural sciences. In fact, better understanding of plant physiology and genetics can possibly be used to enhance biological processes such as N fixation, nutrient use efficiency and plant responses to pests (Doré et al., 2011). Such improvements, in the context of an agricultural system modelled after a natural ecosystem, can contribute to ecological intensification and greater productivity.

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.

SUMMARY AND CONCLUSIONS

Assessment of Farming Practices for their Role in the Sustainable Development of Canadian Prairie Cropping Systems

The farming practices reviewed in this paper represent a wide range of possibilities for the development of Canadian prairie cropping systems. These practices vary in scope from relatively simple modifications to systemic changes that require an entirely different way of viewing agricultural systems. The potential impacts of these practices on the sustainability, profitability, and resilience of prairie cropping systems also vary widely. To assess the potential of each farming practice, ratings were assigned for each of the criteria described in Table 1, along with a measure of the strength of the assessment, based on how much we currently know (Table 2). Together, these ratings can be used to identify farming practices that hold immediate potential for significant impact through widespread implementation, as well as areas that have high potential but require more knowledge. Assessment scores were assigned based on potential impact over the whole prairie region, with the recognition that local differences may occur.

The practice with the highest expected impact in all three criteria categories (sustainability, profitability and resilience) is organic systems. Organic systems have well-documented potential for medium to large positive impacts in all areas, due largely to the combination of a number of other practices such as the use of endogenous inputs, diverse crop rotations, perennial forages in rotation, and protection of natural habitat, along with the availability of market premiums to support these practices. However, the widespread implementation and long-term sustainability of organic systems is limited by the export of agricultural products without adequate replacement of those nutrients, leaving nutrient cycles open. This is an issue of local, regional, and global scale that will only be resolved when safe and convenient methods are developed to recycle nutrients in human waste back into food production systems. A more immediate issue is that certified organic systems are currently implemented using a wide variety of practices that do not necessarily allow these systems to live up to their potential for environmental sustainability and resilience. Thus, improved dissemination of information and the provision of incentives for adoption of already-established beneficial practices could result in major and immediate improvements in these systems. Overall, a more ecological understanding of organic systems also has great potential to improve the productivity and further enhance the sustainability and resilience of these systems.

Practices that have high ratings in two of three areas include perennial forages, perennial grains, integrated crop-livestock systems and farmscaping. Perennial forages in particular have a large and well-documented positive impact on many of the environmental sustainability and resilience criteria and are also technically feasible. Adoption of perennial forages in rotation is already high in certain areas of the prairies, where soils and climates are less suited to annual cropping. However, convincing farmers in prime annual cropping areas to include forages in rotation appears to be difficult. Again, an ecological understanding of the role of perennials in systems, along with a move to integrated crop-livestock systems in which forages have economic value, would reinforce the benefits of perennial forages in rotation. Growing interest in and consumer demand for grass-fed beef and other pastured livestock products could create further incentives to include perennial forages, while creating protectable advantages for these products.

Table 2. Assessment of farming practices for their potential role in the sustainable development of Canadian prairie cropping systems. 1=no impact; 9=very large impact. Letters following number ratings indicate the strength of the assessment (S=strong; M=moderate; W=weak).

Criteria	Varieties and genetics	Crop selection and rotation	Cover crops*	Annual polyculture	Perennial forages*	Perennial grains	Tree-based intercropping*	Shelterbelts/ecobuffers	Reducing tillage*	Animal manure	Green manure	Soil biological fertility	Organic systems	Integrated crop-livestock	Farmscaping
Sustainability Criteria															
Soil Health	2 M	4 M	6 S	2 M	8 S	7 M	6 M	7 M	8 S	7 M	7 M	8 S	8 S	6 M	6 M
Soil Erosion	2 W	3 M	7 S	2 W	8 S	8 S	7 M	8 S	8 S	3 M	4 M	3 W	5 S	4 W	6 S
Dewatering Wet Soils	2 W	5 S	7 S	2 W	8 S	8 W	7 W	7 M	2 S	2 W	5 M	2 W	5 M	3 W	5 M
Storing Water in Dry Soils	2 W	5 S	2 W	2 W	2 S	2 W	5 W	7 S	8 S	5 M	4 M	2 W	5 M	3 W	7 M
Water Quality Protection	2 W	2 M	5 M	3 W	8 S	8 W	7 W	7 S	7 S	1 S	5 M	7 W	7 M	4 M	8 M
Air Quality Protection	1 W	2 W	2 W	1 W	2 W	2 W	5 W	8 S	6 W	1 S	1 W	2 W	4 W	5 W	6 M
Natural Pollination Services	2 W	4 M	5 W	4 W	6 M	6 W	5 W	8 S	2 W	1 W	3 W	1 W	7 M	4 W	9 S
Natural Pest Suppression	5 M	5 S	3 M	3 M	6 S	6 M	5 M	6 M	1 M	5 M	5 M	6 M	7 M	5 W	9 W
Natural Disease Resistance	8 S	6 S	2 M	5 S	3 M	6 M	4 W	4 W	1 M	5 M	3 W	6 M	7 M	4 W	5 M
Greenhouse Gas Emissions	1 M	4 M	5 W	2 W	8 S	8 W	5 M	5 M	5 M	3 S	6 M	6 W	7 S	7 M	6 W
Carbon Sequestration	1 M	2 W	5 W	1 W	7 S	7 W	8 S	7 S	6 S	5 M	5 M	6 W	6 S	6 M	7 M
Nutrient Management	3 M	5 S	6 S	4 S	8 S	6 M	5 M	5 W	3 S	8 S	8 S	8 M	8 S	8 S	6 W
Profitability Criteria															
Profitability	4 S	6 S	5 M	3 M	7 S	5 M	5 M	5 M	7 S	3 S	5 S	5 W	7 S	8 S	5 M
Protectable Advantages	5 S	2 W	1 W	1 W	4 M	4 W	1 M	1 W	1 W	1 W	1 W	1 W	7 S	5 W	5 W
Income Stability / Reduced Risk	3 M	6 S	2 W	4 M	6 M	7 M	5 M	4 M	3 M	4 W	5 M	5 W	5 M	7 M	6 W
Resilience Criteria															
Resilience to Climate Extremes	5 M	6 M	5 M	4 M	7 M	7 M	5 M	7 M	5 M	5 M	4 M	5 W	5 M	6 W	7 M
Energy Use/Efficiency	1 M	4 S	4 M	3 M	8 S	8 M	5 W	5 W	5 S	5 M	5 S	8 M	7 S	6 M	6 W
Enterprise Diversity	2 M	5 S	2 M	3 M	7 S	7 W	7 S	5 M	2 M	2 W	2 W	2 W	6 S	8 S	6 M
Agro-ecological Integrity	1 W	5 M	6 M	4 M	7 S	7 S	7 S	7 S	4 M	7 M	7 M	8 S	6 S	8 S	8 S
Adaptive capacity	3 W	5 M	3 M	3 W	6 W	6 W	6 M	5 M	4 S	5 M	5 M	5 W	6 S	8 S	6 M
Operational Criteria															
Technical Feasibility	9 S	8 S	5 M	5 M	8 S	1 S	4 W	8 S	8 S	7 S	8 S	3 W	5 M	6 M	4 M
Adoptability	9 S	7 S	3 W	2 S	5 S	1 W	2 W	4 M	5 S	3 S	2 M	2 W	2 S	3 M	4 W

* Assessment scores for these practices may differ in wet vs. dry areas of the prairies.

For perennial grains, crop-livestock systems, and farmscaping, the concepts have received considerable attention and exhibit a great deal of potential. However, applied research on integrated crop-livestock systems and farmscaping is still in its infancy, especially in the prairie region, and implementation of perennial grain systems is impossible until varieties become commercially available. 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. Documentation and in-depth study of these existing examples could provide a valuable foundation for continued research on crop-livestock and farmscaping management practices that are practical and feasible for prairie farmers. Development of interdisciplinary research teams among existing government and university researchers specializing in the various components of these integrated systems is also needed.

Crop selection and rotation, cover crops, agroforestry practices (tree-based intercropping and shelterbelts/ecobuffers), reducing tillage, animal and green manures, and soil biological fertility received moderate overall ratings. Of these, crop rotation, reducing tillage, and shelterbelts are best understood and also have relatively high ratings for operational criteria. Indeed, these practices are already common across the prairies. However, optimal use of crop rotation may be limited by poor markets for all but a few crops, which causes farmers to shorten their rotations. The reliance of no-till farming on herbicides limits the sustainability of this practice; however, a shift to the more holistic system of conservation agriculture, with its emphasis on crop diversity and cover crops along with reduced soil disturbance, would be a positive step. Incentives may be required to convince farmers to diversify their rotations and include cover crops until the benefits of these systems become more broadly apparent. The long-standing importance of field shelterbelts on the prairies has been diminished in recent years as a result of increasing field equipment size and a perceived reduced risk of wind erosion due to no-till practices. Increased documentation of the positive role of shelterbelts and multi-functional ecobuffers and dissemination of this information is needed to protect the shelterbelts that remain, encourage their rejuvenation and promote establishment of new ones.

Cover crops and tree-based intercropping systems are practices that are little used on the prairies currently. Finding a temporal niche for cover crops in the short growing season of the prairies remains a challenge. Novel ways of looking at cover crops, perhaps in conjunction with crop-livestock systems where cover crops would also provide forage, are likely necessary to promote implementation of this practice. Tree-based intercropping requires development of locally adapted systems and demonstration of the benefits to convince farmers to modify their field structure to include trees. While the primary area of application for cover crops and tree-based intercropping may be in the wetter zones of the prairies, opportunities exist to develop systems that fit dryer regions as well. For instance, as already mentioned, cover crops could allow prairie no-till systems prevalent in dryer areas to move to a more integrated conservation agriculture approach.

Farming practices with the lowest expected impact on sustainability, profitability and resilience included crop varieties and genetics and annual polyculture. In addition, the impact of these practices on sustainability criteria in particular appears to be poorly understood. For annual polyculture, low ratings are a result of poor success so far in developing successful mixtures for field-scale temperate cropping systems. Because the success of particular annual polycultures is likely location specific due to the effects of soils and weather on crop resource use and competition dynamics, farmer experimentation and local demonstration of polycrop options may

be more likely to make progress in the development of successful systems than centralized research. For crop varieties and genetics, the generally low impact ratings for sustainability and resilience criteria are due to the relatively low likelihood that improved varieties will make substantial improvements in these areas. Nonetheless, the potential for natural disease and pest suppression and resilience to climate extremes are notable exceptions that warrant further investigation and development. The current lack of knowledge on sustainability and resilience impacts of crop genetics is due to an emphasis in crop breeding programs on yield, ease of management, and quality traits, rather than on broader, long-term goals. A shift in priorities could allow for the extensive crop breeding infrastructure already in place to focus on developing varieties that are well suited to ecologically-based cropping systems.

Based on the strength of our assessments, it is possible to identify components of environmental sustainability, profitability and resilience that are well understood or, conversely, where knowledge appears to be lacking. Criteria that have received considerable attention (receiving a large number of "strong" ratings) include soil erosion, nutrient management, profitability, and agro-ecological integrity (Table 2). Well-developed knowledge on soil erosion, nutrient management and profitability may be linked to the development of direct and immediate negative consequences as a result of poor management in these areas, making them obvious priorities for research. The strength of knowledge in the area of agro-ecological integrity is a result of more recent interest in such systems through the development of agricultural ecology; our knowledge of agro-ecological integrity remains largely at a conceptual level so far and next steps will require more thorough and locally relevant application of these concepts. Criteria that are poorly understood (large number of "weak" ratings) include air quality protection, natural pollination services, and protectable advantages (Table 2). Lack of knowledge on air quality and natural pollination services may be related to inherent research challenges such as the complexity of linking air quality to specific practices and the difficulty in quantifying natural pollination services. While the general idea of protectable advantages is not new, strategic development of this concept is relatively recent and has not yet been applied with rigour to agricultural systems.

Priorities for Canadian Prairie Cropping Systems

Ecologically-based farming systems have the potential to enhance the environmental sustainability, profitability and resilience of Canadian prairie cropping systems. These systems, in which biological processes are recognized for their important role in maintaining function of the system, offer a framework in which to understand the role of all other farming practices. In such systems, the priority is shifted away from narrow consideration of only crop yields and net returns, and encompasses broader goals of ecological and social importance. These holistic goals are fundamental to the long-term success of any sector or society.

Within this ecological approach to agriculture, there is room for a wide variety of individual farming practices. A focus on key sustainability and resilience indicators, including the protection and enhancement of soil health, nutrient management based on soil biological fertility and recycling within the system, and consideration of agro-ecological integrity, can guide the development of locally adapted, knowledge-based systems. More specifically, practices that allow for inclusion of more advanced successional states (i.e. perennials and trees/shrubs); rely on nutrient cycling, biological N fixation and soil biological fertility (i.e. use of green manures, animal manures, and soil-building practices); and purposefully augment the agricultural and natural biodiversity of the system (i.e. crop-livestock integration, ecobuffers,

farmscaping) have the greatest potential as components of environmentally sustainable and resilient cropping systems. Profitability of these systems will depend in part on the choice of agricultural species in these systems, optimization of synergies among system components, and perhaps development of strategies that lead to protectable advantages. A shift to ecological agricultural systems would motivate more specific attention to the interactions between system components and the potential consequences of changing a specific practice on other system components.

Management of diversified, ecologically-based farming systems requires a dynamic, knowledge-based approach tailored to local circumstances, rather than a prescriptive, input-based approach. Moving to such a system does not preclude the use of inputs but relies on farmer knowledge of local ecological processes to make the best use of whatever inputs are used. Ecological farming systems with multiple, integrated farm components would require farmers to have advanced organizational and system management skills and highly developed marketing abilities, along with specific knowledge of various production systems. Cooperation among local groups of farmers and other entrepreneurs could allow individuals to cultivate their own strengths while participating in diverse farming systems and contributing to vibrant local economies. Development of such systems requires effective extension and education programs founded on an ecological understanding of agricultural systems, as well as support to farmers through local production and market research and facilitation of connections between complementary farms and businesses. Advancement of farmer knowledge and local business initiatives in this way enhances human and social capital in rural areas while simultaneously creating advantages that are difficult for market competitors to imitate.

Creating Conditions for Change

Creating conditions that allow and encourage farmers to adopt beneficial practices is complex and a full discussion of how to implement changes is beyond the scope of this paper. However, it is important to note that adoption of new farming practices has an opportunity cost, as farmers learn how to develop and manage new systems and invest in the knowledge and infrastructure required to implement these systems. The benefits of many ecological farming practices take several years to develop, delaying the return on these investments. Tight margins on most farms mean that even a small-scale failure in a new crop or enterprise could threaten the financial viability of the farm, even though eventual successful implementation of that practice would contribute to long-term profitability. Certain trade-offs, such as the often-observed increase in labour requirements when reliance on fossil fuels is reduced (e.g. Davis et al., 2012), may require adjustments in basic farm operations.

Both formal and informal structures are required to support the adoption of new farming practices. For instance, policies that provide financial incentives and risk management programs for farmers implementing beneficial practices can reduce the financial risk associated with on-farm experimentation and long-term investments. Providing access to resources that are prohibitively costly or not widely available to farmers, such as specialized equipment or plant material for shelterbelts or natural habitat plantings, at a subsidized rate is also a powerful tool for promoting adoption of beneficial practices. Educational programs on ecological agriculture and demonstration projects on promising practices, led by extension personnel with a vision for sustainable and resilient agriculture and trained in designing and implementing such systems, would raise awareness of the need for a new approach to agriculture and the possibilities that it

may offer, while independent farm production extension services would help to provide the support necessary for farmers to implement innovative practices. Farmer organizations and informal farmer groups already have effective communication networks that facilitate the exchange of information; support for such groups would be a valuable investment in the social capital of rural communities while promoting dissemination of knowledge at a grass-roots level.

Development of knowledge related to ecological agriculture is fundamental to the successful implementation of these systems. Current research efforts in the prairie provinces are typically highly specialized and are often industry driven. This has resulted in a reductionist approach to solving agricultural problems, focused primarily on short-term goals. Even the research dedicated to sustainability has focused mainly on efficiency of input use and mitigation of negative consequences of existing and dominant agricultural production systems. A long-term vision of sustainable development, on the other hand, requires an approach that encompasses the broader goals of social and environmental sustainability. This also requires a different approach to research, in which the interactions and emergent properties that develop among system components are, at the very least, acknowledged and, ideally, investigated.

The study of local natural ecosystems and the key processes that contribute to their health is a key starting point for effective development of ecologically-based agricultural systems. For instance, understanding the roles of perennial herbaceous vegetation, grazing ruminants, localized woody vegetation, and both seasonal and permanent wetlands and waterways in the function of prairie ecosystems can set the stage for development of farming systems that harness natural processes to become highly productive while maintaining ecosystem services. Building on this knowledge requires research that is holistic and truly interdisciplinary, operating on a long-term temporal scale and a landscape-level spatial scale. Long-term farming systems trials would allow for examination of emergent properties and provide an essential framework for the development of more specific questions regarding the optimization of these systems, while informing policy and program developers of the costs of transition to more sustainable and resilient production systems. Establishment of working experimental farms in various locations across the prairies would create the physical infrastructure required for holistic research while also serving as demonstration sites for sustainable and ecological farming practices. Advances in plant sciences and genetics could also play an important role in the development of ecological farming systems if applied in a holistic context. While such research is necessarily complex, research processes have been proposed that allow for investigation of systems such as those integrating crops and livestock or otherwise mimicking natural ecosystems (e.g. Tanaka et al., 2008; Phelan, 2009; Malézieux, 2012). A realignment of priorities among research programs across the prairies to focus on integrated research could result in significant advances in the development of ecological farming knowledge without requiring major increases to total research resources.

While it is generally accepted that certain farming practices provide environmental, ecological, or economic benefits, the scale of those benefits under varying local soil and climate conditions is not always well understood and is another area that deserves further research. For example, little is known about how the benefits of crop-livestock integration in Manitoba's Interlake region compare to those in dryland cropping systems of southern Alberta, or on how the benefits of crop-livestock integration compare to the benefits of tree-based intercropping in either of these regions. Prioritization of best management practices for specific regions first requires accurate quantification of the benefits and costs of adoption of these practices under local conditions in those regions.

Because of the knowledge-intensive nature of moving to ecologically-based agricultural systems, the transition process may be a slow one, both for individual farmers and the prairie farming system as a whole. In many ways, gradual adoption of beneficial practices, beginning with those that are better understood and easier to implement, can ease the transition and result in greater success. On the other hand, a complete redesign of an agricultural system may be necessary to fully realize the synergies that occur within ecological agriculture. For example, both nutrient dynamics and economic viability of perennial forages, green manures and cover crops are enhanced when they are implemented within the context of an integrated crop-livestock system. Similarly, farmscaping practices such as establishment of ecobuffers and seasonal wetlands to promote biodiversity can become important components of nutrient management systems as deep-rooted trees bring nutrients to the surface and excess nutrients escaping from cropland are captured by wetland vegetation. Thus, a holistic understanding of the interactions among system components provides an essential framework for the implementation of a diverse set of beneficial farming practices.

Regarding agricultural systems as ecological systems requires a major paradigm shift of the sort that is generally only achieved once the existing model ceases to serve its purpose (Phelan, 2009). Our existing model of industrial agriculture continues to function for the time being but is showing signs of wear and tear, as discussed in the introduction of this paper. Issues such as loss of pollinator species, escalating pressure from herbicide tolerant weeds, and contamination of water bodies with nutrients and pesticides may appear to be anomalies that can be solved through tweaking of existing practices; however, there is growing evidence that the existing system is fundamentally unsustainable and that a move to ecologically-based agriculture is not only desirable, but necessary. The concepts of ecological agriculture are becoming increasingly well established, and with increased allocation of resources to research and extension in this area, development and implementation of locally adapted ecological farming systems for the Canadian prairies would be achievable. A proactive move in this direction would provide a solid foundation for the development of environmentally sustainable, profitable and resilient agricultural systems in western Canada.

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