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Integration of perennial forage seed crops for cropping systems resiliency in the Peace River region of western Canada

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Abstract

The Peace River region is one of the northern agricultural frontiers in Canada, undergoing farmland expansion as well as intensification with input-intensive industrial agriculture. The cropping systems evolved with the rotations between annual grain and perennial forage crops as a prudent adaptation to fragile, crust-forming, runoff-prone, poorly developed, platy-structured acidic Luvisolic soils. In recent years, there is a decline in the acreage of perennial forage seed crops leading to simplified low-diversity cropping systems with heavy reliance on external inputs. The production systems have been prone to the rapid evolution of herbicide-resistant weeds, and outbreaks of crop diseases and insect pests in the face of global warming. A number of studies conducted in the Peace River region and other parts of North America have shown multiple benefits of integrating perennial forage crops in the cropping systems. By virtue of high root-to-shoot ratio and perennial growth, forage seed crops can provide multiple ecological services in the fragile Luvisolic soil through increased soil organic matter, carbon sequestration, soil biological diversity, soil structural improvement, nutrient mobilization, crop protection and environmental health, thereby creating conducive effects to the resilient performance of the cropping systems. This review discusses the merits of crop rotations in general and those of perennial forage seed crops in particular in the face of changing climate, with special reference to studies conducted in the Prairies and Peace region of western Canada. Research opportunities are highlighted to elucidate multidimensional ecosystem services from diversified cropping sequences integrating perennial forage seed crops.

Key words: boreal, forage, seed crops, crop rotation, Peace River region

Résumé

Au Canada, la région de la rivière de la Paix marque une des limites les plus nordiques de l'agriculture. Les terres arables continuent de s'y étendre et l'agriculture industrielle s'y intensifie grâce à l'usage massif d'intrants. Les systèmes culturaux ont évolué et la prudence a voulu qu'on adopte des assolements annuels de céréales et de plantes fourragères vivaces en raison de la fragilité du sol, constitué de luvisols acides, mal développés, à structure lamellaire, qui forment des croûtes et sont sensibles au ruissellement. Depuis quelques années cependant, on assiste à une diminution de la superficie consacrée à la production de graines de plantes fourragères vivaces et à l'avènement de systèmes culturaux plus simples, moins diversifiés, qui reposent lourdement sur l'apport externe d'intrants. Avec le réchauffement climatique, pareils systèmes favorisent l'apparition rapide d'adventices résistantes aux herbicides, mais aussi de maladies et d'infestations de ravageurs. Plusieurs études réalisées dans la région de la rivière de la Paix et ailleurs en Amérique du Nord ont illustré les nombreux avantages de l'intégration de plantes fourragères vivaces aux systèmes culturaux. En raison de leur rapport racines:pousses élevé et de leur caractère vivace, les cultures grainières de plantes fourragères pourraient améliorer de diverses manières l'écologie fragile des luvisols (hausse de la quantité de matière organique, séquestration du carbone, diversité de la biologie du sol, amélioration de la structure du sol, mobilisation des éléments nutritifs, protection des cultures, vitalité de l'environnement), ce qui rendrait les cultures plus résilientes. Les auteurs examinent les avantages de l'assolement en général et des assolements de culture grainière de plantes fourragères en particulier face au changement climatique, en faisant spécialement référence aux études réalisées dans les Prairies et la région de la rivière de la Paix, dans l'Ouest canadien. Ils signalent les possibilités de recherche qui permettraient d'élucider les services multidimensionnels à l'écosystème attribuables à la diversité des séquences culturales qui intègrent la production des graines de plantes fourragères vivaces. [Traduit par la Rédaction]

Mots-clés : boréal, fourrage, cultures grainières, assolement, région de la rivière de la Paix

1. Introduction

Many studies have investigated the agronomic, economic, and agroecological dimensions of crop rotations. However, most crop rotation-related studies focus on a few annual crops and usually for a short rotation cycle (Soon et al. 2005; Kirkegaard et al. 2008; Smith et al. 2013; MacWilliam et al. 2014; Angus et al. 2015; Harker et al. 2015; Gill 2018). While some studies involved both annual and perennial crops (Hoyt and Leitch 1983; Hoyt 1990; Diebel et al. 1995; Broersma et al. 1997; Entz et al. 2002; DuPont et al. 2014), there is a dearth of studies involving both annual crops and perennial forage seed crops (Rice 1980; Van Vliet and Hall 1991; Chescu 2003).

Cropping sequence diversification can have multidimensional agroecological impacts including soil conservation (Van Vliet and Hall 1991), soil structure development (Pawluk 1980; Broersma et al. 1997), nitrogen fixation and mineralization (Rice 1980; Broersma et al. 1996), impairment in crop disease cycle (Soon et al. 2005), enhanced stress resistance (Degani et al. 2019) and thereby yield-enhancing effects to succeeding crops (Hoyt and Leitch 1983; Hoyt 1990), economic profitability (Smith et al. 2013) and environmental quality (MacWilliam et al. 2014). Consequently, crop diversification contributes to the enhanced resilience of production systems (Lin 2011) and buffering against market uncertainty (Diebel et al. 1995). In the ecosystems services paradigm (Zabala et al. 2021), crop rotations with perennial forage seed crops generate multiple services that fall under provisioning services (seed and forage biomass production), regulating services (improving soil and environmental health) and cultural/aesthetic services (source of groundcover and greeneries).

This review covers the issues pertaining to simplified agroecosystems, and the role of cropping systems and landscape diversity in enhancing resiliency in the face of climate change. The focus of this review is on major agroeconomic and agroecological outcomes of cropping sequences integrating forage seed crops with special reference to the Peace River region of western Canada. Contextual studies from other parts of Canada and North America are also referenced.

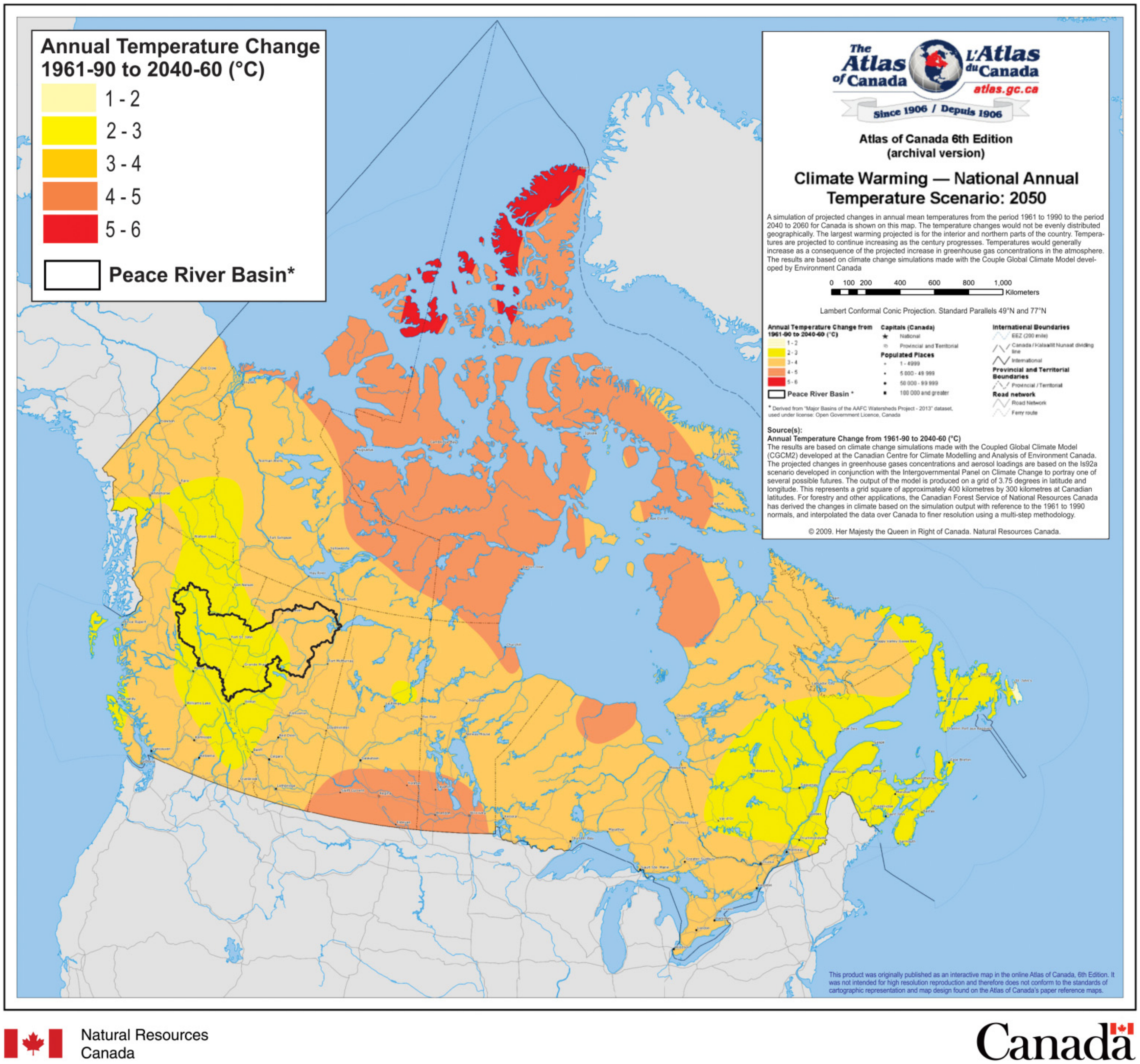
2. Physiography and climatic trends in the Peace River region

It is predicted that climate change resulting in the increase in growing degree days will cause a gradual northward shift in the agricultural climate zone. The increase in growing degree days is predicted to make 55%–89% of the boreal region feasible for cropping by 2099 (King et al. 2018). The Peace River basin of western Canada, spanning between 53.09°–59.64°N and 111.10°–127.10°W, falls in the Boreal Plains ecozone (ESWG 1996) (Fig. 1). The basin's landscape stretches between 400 and 2800 m altitude above mean sea level, with a drainage area of 101 000 km^2 (Najafi et al. 2017) which is just 2000 km^2 smaller than Iceland (Eiríksson and Símonarson 2021). This region extends from the Peace River Country of British Columbia in the northwest to the Peace–Athabasca Delta in northern Alberta. The region stretches into multiple ecoregions presenting the diversity of climate, topography, soils, vegetation, wildlife, and economic activities. The Peace Lowland with subhumid low boreal eco-climate is the major agriculturally significant ecoregion with about 45% of arable land, where various small grains annual crops and forages are grown. Predominantly Gray Luvisolic soils are interspersed with Dark Gray Luvisols, Solonetzic, and Chernozemic soils in the ecoregion (ESWG 1996). Based on earlier reports, the mean summer and winter temperatures are 13 °C and −14 °C, respectively, with mean annual precipitation ranging between 350 and 600 mm (ESWG 1996) and frost-free periods of 100–117 days between mid-May to mid-September (Longley 1967). Analyzing the meteorological data from 1940 to 1997, Cutforth et al. (2004) found significant trends of increasing frost-free periods, but did not provide the specific number of frost-free days. A more recent climatic summary of the Peace River basin during 1961–2005 shows the average minimum and maximum temperatures at −36.6 °C and 27.7 °C, with annual precipitation of 761 mm, of which 51% falls as snow (Najafi et al. 2017). Berry (1991) compared the average annual temperatures of the 1950s to the 1980s in the Canadian prairies and found that the Peace River region is amongst the locations where the largest temperature increase occurred. Over the 100-year period from 1901 to 2002, May to August precipitation in the Peace Lowland increased by 26% (Shen et al. 2005). In the same period, there is a trend of an earlier last-spring-frost and later first-fall-frost resulting in an increase in the frost-free period by 41 days and an increase in growing degree days (Shen et al. 2005). Analyzing the historical data between 1910 and 1997, Cutforth et al. (2004) found that the Peace River region of northern Alberta and northern British Columbia had the largest trends for earlier last-spring-frost dates and an increase in frost-free season across the Canadian Prairies. The analyses showed trends of greater change from 1940 to 1997 compared with 1900 to 1997 (Cutforth et al. 2004). This is an indication of the warming climate, which may open up new opportunities for agricultural production in the region (Weber and Hauer 2003; Motha and Baier 2005).

3. Evolving agriculture and dwindling forage seed acreage

Since the beginning of settlement from the last quarter of the 19th century (Guitard 1965), the Peace River region has evolved as one of the major agricultural domains in Canada (Kerr and Cihlar 2003; Feinstein 2010). Farmland has been continuously expanding with some conversion back from farmland to other land uses (Haarsma 2014; Ruan et al. 2016; Chowdhury et al. 2021). Since the early 20th century, forage seed crops were adopted as keystone crops rotated with small grain annual crops in the cropping systems (Stewart 1933; Guitard 1965; Broersma et al. 1997). Peace River region was reputed to be one of the world's largest producers of turf and forage seeds, accounting for about 30% (recent) to 53% (in early 2000) of total forage seed acreage in Canada (Wong 2017). Until 2000, there were at least nine forage seed processing operations active in the area. A large proportion of the turf and forage seeds are destined for the USA, Europe, and Asia comprising more than 30 countries in the world.

Fig. 1. Map of Canada showing projected annual temperature change from 1961–1990 to 2040–2060 (base map source: "Climate Warming—National Annual Temperature Scenario: 2050", courtesy of Atlas of Canada 6th Edition—archival version; https://open.canada.ca/data/en/data set/cb8843b0-8893-11e0-9f72-6cf049291510). The Peace River region of western Canada is delineated in the map based on the Peace Basin data subset derived from data set of Agriculture and Agri-Food Canada under Open Government License, Canada.



However, in recent years, the turf and forage seed supplies from the Peace River Region are dwindling despite the abundance of the export market and higher price quotes offered for selected forage seed commodities produced in this region. There was a substantial decrease in the number of forage seed producers from 1086 to 632 and production acreage from 137 904 to 73 604 ha between 2001 and 2006. This could partly be due to the fact that the forage seed sector lagged in innovations compared to the grain and oilseed sector resulting in motivational shifts of producers from forage seeds to food crops production (Bronson 2015).Development of early maturing crop cultivars with stress-adaptive physiological traits (Bueckert and Clarke 2013), and an increase in frost-free period (Cutforth et al. 2004; Shen et al. 2005) possibly reduced the risk of annual crop production resulting in the expansion in the annual crop acreage. With the increase in annual crop acreage, the current area under forage seed crops ranges from 49 000 to 57 000 ha (Wong 2017).

This transition from forage-integrated cropping sequences to the tight rotation of annual crops can undermine multiple agroecosystems services generated by perenniality (Sanford et al. 2021) and high carbon input in the soil by virtue of high root-to-shoot ratio of forage crops (Bolinder et al. 2007). The forage crops have conducive effects on the Luvisolic soils (Chescu 2003; Wani et al. 1994) which are typified by fragile, poorly developed, platy-structure, prone to surface crust-formation, runoff and erosion (Lavkulich and Arocena 2011). The fragile soils undergoing simplified rotations with high dependence on external inputs may compromise the resilience of production systems (Malézieux 2012; Bowles et al. 2020; Petersen-Rockney et al. 2021). The rapid evolution of herbicide-resistant weeds (Beckie et al. 2020), and outbreaks of crop diseases such as clubroot in canola (Strelkov et al. 2021) and *Fusarium* head blight in wheat (Turkington et al. 2011) in the region may be some of the manifestations of lack of functional diversity in the cropping systems in the face of global warming. While some noncereal grasses were also found to harbour *Fusarium* pathogens, and may act as a reservoir for wheat-infective *Fusarium graminearum* Schwabe species complex, the perennial grasses had undetectable or trace levels of trichothecene mycotoxins (Lofgren et al. 2018). This further implicates the need for functional diversification strategies to reduce disease inoculum in the agricultural landscape. As the Peace River region is undergoing a warming trend (Cutforth et al. 2004; Shen et al. 2005), insect pest pressure is also expected to increase in the growing seasons due to increased overwintering survival and population growth rates (Deutsch et al. 2018). For example, a 1 °C increase from the current temperature could double the risk for infestation of wheat stem sawfly (*Cephus cinctus*) infestation, shifting the region from marginally suitable to favourable environment for various pests including wheat stem sawfly, migratory grasshopper (*Melanoplus sanguinipes* Fabricius) and pea leaf weevil (*Sitona lineatus* L.) (Olfert et al. 2009).

4. Break-crop effect of sequential crops

Crop rotation is an effective approach to increasing cropping systems diversity for multiple agroecological benefits. Individual crops yield higher when alternated with unrelated species in cropping sequences than when grown continuously in the same field. This rotational or break-crop advantage is evident from many studies around the world (Soon and Clayton 2002; Kirkegaard et al. 2008; Angus et al. 2015). Such yield benefits are attributed to various mechanisms including pest suppression, improved nutrient and water use efficiencies, allelopathy, and changes in rhizosphere biology and soil structure. A number of studies conducted in the Peace River region and Luvisolic soils have shown diverse benefits of integrating perennial forage crops in the cropping systems. Those benefits include soil conservation (Van Vliet and Hall 1991), soil structure development (Pawluk 1980; Broersma et al. 1997), nitrogen fixation and mineralization (Rice 1980; Broersma et al. 1996), disruption of crop disease cycle (Soon et al. 2005; Kutcher et al. 2013) and thereby yield-enhancing effects to succeeding crops (Hoyt and Leitch 1983; Hoyt 1990) (Table 1). Preceding crops with more contrasting plant architecture and functional groups engender better rotational effects on the following crops. For example, the mean yield increase of wheat varied from 0.5 t ha^{-1} after oats to 1.2 t ha^{-1} after grain legumes, while other broadleaf crops such as canola, mustard, and flax had intermediate effects on the following wheat crop (Angus et al. 2015). The magnitude of the break-crop effect declines if the same crop is grown sequentially for two consecutive seasons. The break-crop effect of legumes and nonlegumes broadleaf species on the second wheat crop in the sequence was about 60% and 20%, respectively, of the magnitude of the effect on first wheat crop. Two successive break-crops resulted in 0.1–0.3 t ha^{-1} higher yield than after a single break-crop (Angus et al. 2015). Evidently cropping systems diversification through proper sequencing of crops have a significant yield advantage.

A recent study in a loamy Luvisol in the Peace River region showed that one or two break-crops of pea, barley, or flax resulted in a 19.4% increase in canola yield and a 7.2% increase in wheat yield in comparison to the tight rotation of canola and wheat (Gill 2018). Similarly, canola flanked with two break-crops in rotation yielded 22% higher compared with continuous canola (Harker et al. 2015). A total of 174 comparisons by Hegewald et al. (2018) showed that two break-crops contributed to the yield benefit of succeeding oilseed rape by over 600 kg ha^{-1}, which were attributed to the reduction of pressures of insect pests, diseases, and weeds. In the Canadian Prairies, about 65% of the cropping is practiced with no-tillage seeding (May et al. 2020). Under the no-tillage system, the transition from perennial forage legume seed crops to annual crops had a substantial yield advantage. In a recent study conducted at Beaverlodge in the Peace River region, an unfertilized wheat crop preceded by a biennial stand of red clover or alsike clover produced yield increases of up to 45% compared to wheat crop preceded by 2 years' sequences of annual crops. Similarly, canola after the wheat crop preceded by clovers in the sequence yielded 40%–70% higher than those from annual crop sequences (Khanal et al. 2021). However, the transition from perennial grass seed crops to annual crops under a no-tillage system may not have a break-crop advantage for the immediate following crop (Khanal et al. 2021) due to a high carbon-to-nitrogen ratio (C:N) causing slow decomposition of grass residues and root materials (Livesley et al. 2016). However, perennial forage crops with nearly four-times higher root-to-shoot ratio relative to annual crops (Bolinder et al. 2007; Thiagarajan et al. 2018) can increase soil carbon stock under crop rotation leading to improvement in soil health in the long run (Dheri et al. 2022).

5. Contribution to soil and environmental health

Integration of perennial grass seed crops in the annual crop rotation can contribute to soil conservation and structural improvement. The agroecological importance of forage crops in Canadian Prairies was recognized as early as the 1930s (Stewart 1933). A 6-year crop rotation integrating a 3-year perennial seed crop of creeping red fescue followed by annual crops had 35% less runoff and 400% less soil erosion compared to annual cropping sequences (Van Vliet and Hall 1991). High root-to-shoot ratios of perennial forage crops (Bolinder et al. 2007; Thiagarajan et al. 2018) have the potential to overcome the inherent agronomic constraints of Gray Luvisolic soils typified by weak platy-structured surface horizons underlain by compact subsoils (Lavkulich and Arocena 2011). On this soil type, raindrops disperse soil particles packing them

Table 1. Select examples of agroecological merits of crop rotational diversity pertinent to Canadian Prairies and Peace River region of western Canada.

Cropping systems	Rotational effect Yield advantage	Magnitude of effect Grain yield gain	Study context	Reference
Oats—wheat sequence	Wheat yield advantage over wheat—wheat sequence	0.53 ± 0.14 mean ± S.E. (Mg ha^{-1})	Review of wheat-based cropping systems	Angus et al. (2015)
Canola—wheat sequence	Wheat yield advantage over wheat—wheat sequence	0.80 ± 0.17 mean ± S.E. (Mg ha^{-1})	Review of wheat-based cropping systems	Angus et al. (2015)
Lupin—wheat sequence	Wheat yield advantage over wheat—wheat sequence	1.61 ± 0.45 mean ± S.E. (Mg ha^{-1})	Review of wheat-based cropping systems	Angus et al. (2015)
Pea—wheat sequence	Wheat yield advantage over wheat—wheat sequence	0.52 ± 0.01 mean ± S.E. (Mg ha^{-1})	Fort Vermillion, Alberta, Canada (58°23′N, 116°2′W)	Soon and Clayton (2002)
Red clover—wheat sequence	Wheat yield advantage over wheat—wheat sequence	0.51 ± 0.21 mean ± S.E. (Mg ha^{-1})	Fort Vermillion, Alberta, Canada (58°23′N, 116°2′W)	Soon and Clayton (2002)
Red clover—red clover—wheat sequence	Wheat yield advantage over wheat—canola—wheat sequence under unfertilized condition	1.81 ± 0.29 mean ± S.E. (Mg ha^{-1})	Beaverlodge, Alberta, Canada (55°11′N, 119°18′W)	Khanal et al. (2021)
Alsike clover—alsike clover—wheat sequence	Wheat yield advantage over wheat—canola—wheat sequence under unfertilized condition	1.60 ± 0.29 mean ± S.E. (Mg ha^{-1})	Beaverlodge, Alberta, Canada (55°11′N, 119°18′W)	Khanal et al. (2021)
One or two break-crops of canola, pea, flax barley between wheat	Wheat yield advantage over wheat—wheat sequence	0.33 ± 0.26 mean ± S.E. (Mg ha^{-1})	Donnelly, Alberta, Canada (55°39′38.43″N, 117°6′10.64″W)	Gill (2018)
One or two break-crops of wheat, pea, flax, barley between canola	Canola yield advantage over wheat—wheat sequence	0.63 ± 0.30 mean ± S.E. (Mg ha^{-1})	Donnelly, Alberta, Canada (55°39′38.43″N, 117°6′10.64″W)	Gill (2018)
Alfalfa—8 crops of wheat	Wheat yield advantage over Fallow—wheat sequence without N fertilizer	66%–114% for 8 crop years	McLennan, Alberta, Canada (55.72°N, 116.90°W)	Hoyt (1990)
Forage legumes for 3 years—barley for 7 years	Barley yield advantage over continuous barley without N fertilizer	3.37 ± 0.42 mean ± S.E. (Mg ha^{-1}) for 7 year period	Peace River region, Alberta	Hoyt and Leitch (1983)
Wheat—pea—canola sequence	Canola yield advantage over continuous canola	0.58 ± 0.14 mean ± S.E. (Mg ha^{-1})	Peace River region and Prairies, Canada	Harker et al. (2015)
Oat—oat—canola	Canola yield advantage over 3 year continuous canola sequence	0.22 ± 0.16 mean ± S.E. (Mg ha^{-1})	Beaverlodge, Alberta, Canada (55°11′N, 119°18′W)	Soon et al. (2005)
Two-year break—oilseed rape	Oilseed rape yield advantage over continuous oilseed rape	0.64 ± 0.10 mean ± S.E. (Mg ha^{-1})	Review of 174 comparisons from oilseed rape based crop sequences	Hegewald et al. (2018)
Red clover—red clover—wheat—canola sequence	Canola yield advantage over wheat—canola—wheat—canola sequence under unfertilized condition	1.07 ± 0.23 mean ± S.E. (Mg ha^{-1})	Beaverlodge, Alberta, Canada (55°11′N 119°18′W)	Khanal et al. (2021)
Alsike clover—alsike clover—wheat—canola sequence	Canola yield advantage over wheat—canola—wheat—canola sequence under unfertilized condition	1.14 ± 0.23 mean ± S.E. (Mg ha^{-1})	Beaverlodge, Alberta, Canada (55°11′N 119°18′W)	Khanal et al. (2021)
Cropping systems	**Soil conservation and water use efficiency**	**Magnitude of effect**	**Study context**	**Reference**
Two cycles of summer fallow—canola—barley vs summer fallow—canola—barley—barley underseed to red fescue—fescue—fescue	Runoff reduction due to red fescue perennial seed crop: 229 vs 172 mm annual runoff	57 mm (33%) less annual runoff under fescue-based rotation	Fort St. John, BC, Canada	Van Vliet and Hall (1991)

Table 1. (*continued*).

Cropping systems	Soil conservation and water use efficiency	Magnitude of effect	Study context	Reference
	Reduced soil erosion due to red fescue perennial seed crop: 4.88 vs 1.015 t ha^{-1} annual soil loss	3.86 t ha^{-1} (380%) less annual soil loss under fescue base rotation	Fort St. John, British Columbia, Canada	Van Vliet and Hall (1991)
Wheat—forage grasses and wheat—barley	Forage crops had higher water use efficiency of dry matter production (kg ha^{-1} dry matter mm^{-1} of water) than barley	Forage grasses: 23–32 vs Barley: 19 kg ha^{-1} dry matter mm^{-1} of water	Carman, Manitoba, Canada (49.5086°N, 98.0017°W)	Chescu (2003)
Cropping systems	**Contribution to soil C stock and reduction in greenhouse gas emission**	**Magnitude of effect**	**Study context**	**Reference**
Perennial forage crops in the cropping systems	Perennial forage crops higher root:shoot ratio than annual crops	Perennials: 0.77–1.11 vs Annual: 0.06–0.23	Various locations in Alberta, Canada	Bolinder et al. (2007)
Perennial forage crops in the cropping systems	Perennial forage crops higher root:shoot ratio than annual crops	Perennials: 0.62–1.21 vs Annual: 0.10–0.42	Compilation of 58 studies in Canada	Thiagarajan et al. (2018)
Maize—Faba bean—perennial forage mixture, and maize—faba bean—spring wheat—industrial rapeseed	Two-year perennial forage mixture phase was nearly twice the sink for atmospheric CO_2 with four times less N_2O emission as compared to annual crops phase	Perennial forage phase: net sink of 8.47 ± 5.64 Mg CO_2-eq. ha^{-1} vs annual crops phase: net source of 3.76 ± 2.45 Mg CO_2-eq. ha^{-1}	Glenlea Research Station, Manitoba, Canada (49.64°N, 97.16°W)	Maas et al. (2013)
Two-year perennial forages—barley	Annual N_2O loss (g N ha^{-1} day^{-1}) from soil under spring barley phase was nearly triple that of average of forage crops phase	Perennial forages phase: 2.12 vs spring barley: 6.07 g N ha^{-1} day^{-1}	Braunschweig, Lower Saxony, Germany	Kaiser et al. (1998)
Perennial grassland to annual crops conversion	Perennial grasslands had three to seven times greater root biomass, and two times greater root length compared with annual crops	Root biomass: 9.4 Mg ha^{-1} vs 2.5 Mg ha^{-1}; root length: 52.5 km m^{-2} vs 24.0 km m^{-2}	North Central Kansas, USA	DuPont et al. (2014)
Cropping systems	**Soil structural development and stability**	**Magnitude of effect**	**Study context**	**Reference**
Continuous barley vs 3 years of barley followed by 3 year of forage (mixture of bromegrass and red clover)	Large aggregate percentage (12.7–38.1 mm dry-sieved): 3.2% vs 4.1% of total soil	0.9% more large type soil aggregates with perennial forages	Beaverlodge, Alberta, Canada (55°11′N 119°18′W)	Broersma et al. (1997)
	Soil structure development: soil aggregated stability (number of drops required to disintegrate an aggregate of 0.17–0.23 g: 22 vs 26	18% more stability of soil aggregates with perennial forages	Beaverlodge, Alberta, Canada (55°11′N 119°18′W)	Broersma et al. (1997)
Cropping systems	**Soil health and fertility enhancement**	**Magnitude of effect**	**Study context**	**Reference**
Wheat—fallow vs barley—hay—hay—wheat—oat sequence	Organic matter content: 2.51% vs 1.95%	28% increase in soil organic matter under diverse crop sequence	Breton, Alberta, Canada (53.08N, 114.44W)	Pawluk (1980)
Forage legumes in the cropping systems	Annual N fixation by alsike clover—forage crop: 22–143 kg ha^{-1}; by seed crop 21 to 120 kg ha^{-1}	Replacement of up to 310 kg urea by alsike clover N fixation	Beaverlodge, Alberta, Canada (55°13′N, 119° 26′W)	Rice (1980)
	Annual N fixation by red clover—forage crop: 17–77 kg ha^{-1}; by seed crop 15–56 kg ha^{-1}	Replacement of up to 167 kg urea by red clover N fixation	Beaverlodge, Alberta, Canada (55°13′N, 119° 26′W)	Rice (1980)

Table 1. (*concluded*).

Cropping systems	Soil health and fertility enhancement	Magnitude of effect	Study context	Reference
Continuous barley vs continuous red clover for 3 years	10-fold greater N mineralization under continuous clover than continuous barley	Potentially mineralizable N 29 vs 364 mg kg^{-1} soil; mineralization rate constant 0.04 vs 0.26 wk^{-1}	Beaverlodge, Alberta, Canada (55°11′N, 119°18′W)	Broersma et al. (1996)
Eight-year diverse annual and perennial crop rotations compared with continuous grain barley cropping	Improvement in several soil property parameters	Diverse vs barley: microbial biomass C 330.5 vs 109, mineral N 28.2 vs 8.1, microbial N 51.4 vs 26.8 μg g^{-1} soil, total N 1.87 vs 1.32 mg g^{-1} soil	Breton, Alberta, Canada (53.08 N 114.44 W)	Wani et al. (1994)
Monoculture and high diversity cropping of forbs and grasses	Perennial grassland with high species diversity had over four-fold more soil carbon and nitrogen than monoculture	16-species mixture: root biomass 1218 ± 54.3 g m^{-2}, C:N ratio 1.6 ± 0.1 vs monoculture: root biomass 381 ± 59.8 g m^{-2}, C:N ratio 10.9 ± 0.12	Cedar Creek Ecosystem Science Reserve, Minnesota, USA	Fornara et al. (2009)
Various annual and perennial cropping systems	Crop rotations with perennial and cover crops increased soil organic carbon (SOC) concentrations relative to annual grain crops-based rotations	Perennial cropped had 6.2% and cover-cropped 12.5% higher SOC than annual cropped	Review of studies using 27 cropping systems sites from world	King and Blesh (2018)

Cropping systems	Pest suppression and cropping systems resilience	Magnitude of effect	Study context	Reference
Canola—canola—canola vs oat—oat—Canola	Brown girdling root rot in canola: incidence: 21% vs 17%; severity 13.4% vs 11.9%	19% less incidence and 7% less severity of root rot under diversified sequence	Beaverlodge, Alberta, Canada (55°11'N 119°18'W)	Soon et al. 2005
Continuous canola vs wheat—pea—wheat—canola	Blackleg disease in canola: incidence 62% vs 31%; severity 2.1 vs 0.8 on a scale of 5	50% less incidence and 62% less severity of blackleg under diversified sequence	Scott and Melfort, Saskatchewan, Canada	Kutcher et al. (2013)
Continuous canola vs wheat—pea—canola sequence	Blackleg disease in canola: incidence 44% vs 19%; severity 0.6 vs 0.3 on a scale of 5	56% less incidence and 50% less severity of blackleg under diversified sequence	Peace River region and Prairies, Canada	Harker et al. (2015)
Continuous canola vs wheat—pea—canola rotation	Root maggot insect pest damage in canola: 2.06 vs 1.99 on a scale of 5	4% less damage	Peace River region and Prairies, Canada	Harker et al. (2015)
Various simple and diverse crop rotations	Decreased weed density and weed biomass in diversified rotations	49% reduction in weed density and 22% reduction in weed biomass than simple rotations	Meta-analysis using 298 paired observations from 54 studies across six continents	Weisberger et al. (2019)

Cropping systems	Economic profitability	Magnitude of effect	Study context	Reference
Pea—canola—wheat sequence compared to continuous canola	The contribution margin of pea—canola—wheat was higher than continuous canola with no fungicide application	Pea—canola—wheat vs continuous canola: \$357 ± 91 vs \$148 ± 89 ha^{-1} yr^{-1}	Scott (52.48N, 108.88W) and Melfort (57.58N, 104.68W), Saskatchewan, Canada	Smith et al. 2013
Pea—canola—wheat sequence compared to continuous pea	The contribution margin of pea—canola—wheat was higher than continuous pea with no fungicide application	Pea-canola-wheat vs continuous pea: \$336 ± 52 vs \$135 ± 99 ha^{-1} yr^{-1}	Scott (52.48N, 108.88W) and Melfort (57.58N, 104.68W), Saskatchewan, Canada	Smith et al. 2013
Oilseed—cereal rotations compared to diversified dry pea and lentil based rotations	Replacement of a wheat crop from canola—wheat—wheat—wheat sequence by leguminous crops of lentil or dry pea resulted in higher gross margin	Net returns over variable costs: dry pea-based rotations \$1372 ha^{-1}, lentil-based rotations \$1278 ha^{-1} vs oilseed-cereal rotation \$1083 ha^{-1}	Life cycle assessment of western Canadian cropping systems	MacWilliam et al. (2014)
Four year sequence of creeping red fescue seed crop—canola compared to wheat–canola repetition	Creeping red fescue-based rotation had higher gross margin than wheat–canola repetition	Gross margin at average price: fescue based rotation \$2763 vs wheat–canola rotation \$2568 in a rotation cycle	Beaverlodge, Alberta, Canada (55°11′N 119°18′W)	Khanal et al. (2021)

into 2–5 μm thick layers of hard consistence leading to the development of a hard crust after subsequent drying (Arshad and Mermut 1988). Integration of grasses in the annual cereal rotation and the use of organic fertilizer had positive effects on the development of discrete granular structures in the soil (Pawluk 1980). Crop rotation with increased plant diversity from one to five species over time resulted in distinct soil microbial communities contributing to increases in soil aggregation, organic carbon, total nitrogen, and microbial activity (Tiemann et al. 2015). Increased rotational diversity imparts diverse biochemical environments in the rhizosphere that sustain soil biological communities enhancing the soil health.

Forage seed crops in rotation add perenniality to and diversify the system. These properties may be associated with higher rotational water use efficiencies of forage seed crops-based sequences compared to the annual crops-based sequences (Chescu 2003) and reduction of greenhouse gas emissions (Kaiser et al. 1998; Maas et al. 2013). For two years of establishment of perennial forage crops in an annual crop rotation, the perennial forages were over twice the sink for atmospheric CO_2, while having nearly three-quarter less N_2O emission compared to the annual crops (Maas et al. 2013). As estimated by Bolinder et al. (2007), about half of the net primary productivity of forages lied belowground with an average shoot-to-root ratio of 1.6, while the average belowground net primary productivity of annual crops was about 20% with a shoot-to-root ratio of above 5.0. Recently Thiagarajan et al. (2018) estimated the average root-to-shoot ratio of pea, barley, wheat, and canola to be 0.211, 0.200, 0.217, and 0.369 within the soil depth of 1 m, while that of forages to be 0.868 with the values of 0.618 in the establishment year and 1.213 in the production years. A long-term and conversion study in the USA showed that perennial grasslands had three to seven times greater root biomass (9.4 vs 2.5 Mg ha^{-1}), and two times greater root length (52.5 vs 24.0 km m^{-2}) compared with cropland. Old roots of proceeding perennial vegetation persisted in the annual crop soil for over 5 years after the conversion of perennial grassland to annual cropland (DuPont et al. 2014). A long-term study by Fornara et al. (2009) showed that perennial grassland with high species diversity had over four times more root biomass than monoculture, with similar values of the C:N ratio. These results suggest higher carbon and nitrogen stock in the high diversity grassland communities than in monoculture systems. Thus, the perennial forages may have a high potential of enriching the belowground carbon pool. The contribution of roots to relatively stable soil carbon pools is estimated to be 2.3 times higher than that of shoot-derived plant material (Kätterer et al. 2011). Increasing the functional diversity of crop rotations that increases carbon input in the soil can lead to an increase in soil organic carbon concentrations (King and Blesh 2018). Therefore, forage crops in the cropping sequences can be instrumental in increasing soil organic carbon, which in turn enhances water holding capacity, infiltration, and microbial activities, rendering the soil more favourable for crop production (Reeves 1997). Soil organic matter is an indicator of soil natural capital that buffers yield variance against adverse weather while reducing reliance on external inputs (Cong et al. 2014).

6. Nitrogen economy with leguminous crops

Integration of leguminous forage crops in the cropping systems enhances soil nitrogen input, mineralization, and structural attributes. Inclusion of forage crops, especially legumes in the crop rotations is conducive to higher productivity of the following crops by virtue of a steady supply of nitrogen, increased soil organic matter, improved soil quality, suppression of arable crop weeds, and disruption of crop disease cycles (Ball 1992; Entz et al. 2002; May et al. 2020). On the Orthic Gray Luvisol in the Peace River region, annual nitrogen fixation by seed crops of alsike clover and red clover was estimated in the range of 20.8–143.0 and 15.3–77.3 kg ha^{-1}, respectively. Alsike clover exhibited higher nitrogen-fixing activities earlier in the growing season than red clover (Rice 1980). A continuous leguminous sequence of red clover had 10-fold higher N mineralization rate than the nonlegume crop sequences (Broersma et al. 1996), while both perennial forage grass and legume-based sequences had greater soil aggregate stability than the annual crop sequences (Broersma et al. 1997). Wani et al. (1994) documented an interesting result of 8-year continuous grain barley that received fertilizer N at 90 kg ha^{-1} compared to an 8-year diverse agroecological rotation. The 8-year agroecological rotation had the following sequences of crops: barley—faba bean—barley—faba bean—barley underseeded to forage mixture (red clover and bromegrass)—forage mixture—forage mixture—forage mixture. The cropping system received both faba bean green manure and manure from livestock fed with forages and faba beans grown in the rotation. Over the eight years, they found an increase in total carbon, nitrogen, and phosphorus, and available nitrogen, phosphorus, and potassium along with an increase in cation exchange capacity, microbial biomass, microbial respiration, and abundance of bacteria, fungi, and mycorrhizae in the diverse agroecological rotation compared with the continuous grain barley sequence (Wani et al. 1994). Beneficial effects of sweet clover in the crop rotation in the Grey Luvisol in the Peace River region were reported nearly 70 years ago (Carder and Hanson 1951). The results of numerous studies conclude that the inclusion of forage legumes in the cropping systems imparts both nitrogen fertility and soil augmenting effects in the Grey Luvisols.

The studies conducted at Beaverlodge in the Peace River region showed that residual effects of preceding perennial leguminous crops could last for several years. Under no supplemental nitrogen application, preceded by alfalfa and a mixture of alfalfa and smooth bromegrass, ten sequential wheat crops interspersed with three summer fallows, produced significantly higher yield than the control without preceding alfalfa. The first eight crops of wheat following alfalfa produced 66%–114% higher yields than those following control (Hoyt 1990). A 7-year study by Franco et al. (2018) compared the performance of continuous wheat cropping fertilized with 67 kg N ha^{-1} relative to wheat crops preceded by alfalfa monocrop and alfalfa + grass mixtures in the cropping sequences. In that study, the fertilized continuous wheat crop yielded similar to the wheat preceded by alfalfa for initial 2 years. In the third, fourth, and fifth years, the wheat crop preceded by alfalfa yielded 19%, 41%, and 23% higher, respectively, than the fertilized continuous wheat crop (Franco et al. 2018). Without supplemental nitrogen, barley grain crops following hay crops of alfalfa, birdsfoot trefoil, alsike clover, red clover, and sweet clover had significantly higher yields than barley following fallow on Gray Luvisolic soils (Hoyt and Leitch 1983). A recent study by Khanal et al. (2021) showed that the biennial legume seed crops of red and alsike clovers could replace nitrogen fertilizer requirements for succeeding sequential wheat and canola crops by at least 90 and 45 kg ha^{-1}, respectively (Khanal et al. 2021). With proper planning of cropping sequences, perennial legume seed crops can enhance the nitrogen economy of the cropping systems.

7. Cropping systems resilience

Crop rotations can limit crop pest numbers and damage. Canola grown after two break-crops in rotation had 54% less incidence of blackleg disease and 6% less damage by root maggot compared with continuous canola (Harker et al. 2015). Similarly, 4-year cropping sequences of wheat–pea–wheat–canola and wheat–flax–wheat–canola had 2.6 times less incidence of black leg disease compared to continuous canola sequence (Kutcher et al. 2013). Soon et al. (2005) reported that canola preceded by two break-crops had a lower incidence of brown girdling root rot and concomitantly higher seed yield than the unbroken sequence of canola. A meta-analysis by Weisberger et al. (2019) using 298 paired observations from 54 crop rotation studies across six continents showed that diversified crop rotations reduced weed density by 49%. When combined with such tactics as zero-tillage and seeding time manipulation, increased diversification had up to a 65% reduction in weed density (Weisberger et al. 2019). Crop rotation continues to be the most effective pest management tool from ancient to modern agriculture.

Weed management, especially herbicide resistance has been a growing concern in the world and the Peace River region of Canada is not an exception (Beckie et al. 2019, 2020; Beckie 2020). Different plant species grown in cropping sequence may have differential effects on weed composition over time (Ball 1992), because of allelopathic interactions, nutrient mobilization and alteration in the soil biota (Bennett and Klironomos 2019). Schmer et al. (2017) reported that preceding annual crops also have a differential influence on the stand establishment and productivity of following perennial crops. Crop management factors such as tillage, herbicide, nutritional and moisture regimes, insect pests, diseases, and various abiotic stress factors modulate the intensity of allelopathy (Einhellig 1996). Therefore, appropriately designed crop rotation is a core beneficial management practice reducing the risk of herbicide resistance (Norsworthy et al. 2012).

8. Economic profitability of crop diversification

Multiple agroecological functions of crop rotation from soil conservation to improvement of soil and plant health ultimately translate into economic benefits to the producers. Smith et al. (2013) found that the profitability of cropping sequences increased with the integration of break-crops of wheat or flax in the continuous canola and pea rotations. Conversely, the rotations that involved continuous cropping of canola and pea had the least profitability. A life cycle and economic assessment study by MacWilliam et al. (2014) revealed that replacement of a wheat crop from canola–wheat–wheat–wheat sequence by leguminous crops lentil and dry pea resulted in higher gross margin accompanied by enhanced resource use efficiency, human health benefits, and reduced global warming effects.

A recent study in the Peace River region compared the relative economic advantage of 4-year crop sequences with and without the inclusion of perennial seed crop of creeping red fescue in the annual cropping systems. Annual crops in the cropping systems included wheat, canola, barley, and peas. The cumulative returns of different 4-year cropping sequences were assessed in terms of canola equivalent yield (price ratio of non-canola to canola multiplied with the yield of canola crop) and gross margins. The creeping red fescue-based sequences had higher canola equivalent yield and gross margins compared to the annual crops-based sequences (Khanal et al. 2021).

Many temperate perennial forage seed crops have a vernalization requirement—a prolonged exposure to cold temperature for reproductive transformation (Ream et al. 2012). This obligation coupled with the slow establishment of perennial crops creates a seasonal lag with no seed production in the year of establishment. To compensate for this seasonal lag, some farmers in the Peace River region underseed clovers and grasses seed crops with annual crops. A number of studies report the use of cereal clover intercropping as forage, companion or cover crops (Schmidt et al. 2003; Thorsted et al. 2006*a*, 2006*b*; Blaser et al. 2006; Gaudin et al. 2013). Gaudin et al. (2013) reviewed the agroecological and economic advantages of red clover interseeded with annual crops. Experience shows that forage seed crops provide the producers with the opportunity for staggering farm operations over the growing seasons. Most of the forage crops produce seeds for multiple years with a single seeding, allowing farmers to invest more time in annual crop seeding in the spring. Forage seed crops mature earlier allowing for an earlier harvest. This provides opportunities to utilize the labour and equipment staggeringly over the season without competing with the time for annual crop harvests. Thus, forage seed crops can provide more opportunity costs for farm labour and better utilization of farm equipment.

9. Conclusions

Integration of perennial forage seed crops in the annual crop rotations enhances the agroecosystem performance in terms of productivity, resilience, and resource use efficiency. There may be some trade-offs to be balanced in the production and marketing processes. However, the agroeconomic and agroecological benefits outweigh the demerits associated with perennial seed crops. The agroecological and economic roles of forage seed crops are significant in agriculture in the Peace River region. However, forage seed crops are yet to get significance in the priority sector policies. Forage seed crop statistics are not easily available. Studies are still lacking on forage seed crops-integrated production systems. There are plenty of opportunities to study the multidimensional aspects of agroecosystems services of forage seed crops-based rotations globally. Those aspects should integrate profitability, risks, and flexibility for producers, carbon sequestration, greenhouse gas emissions, pollination, biodiversity, nutrients and agrochemical leaching, nutrient recycling, soil stabilization and improvement, and responses to stresses.

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The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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