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The story of long-term research sites and soil health in Canadian agriculture

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Abstract

Canada's interest in agricultural lands has changed with time from a desire of crop yields at Confederation through to discussions in the Senate on adaptation and resilience in 2018. Long-term research experiments (LTRs) have been present and utilized by federal and university researchers to provide answers throughout. Here we highlight the importance of LTRs by identifying the historical context of LTRs and soil health research in Canada. We then briefly describe the history and key results from select LTRs and illustrate the wealth of information collected from the North American Project to Evaluate Soil Health Measurements cross-country point-in-time soil sampling from these LTRs. We discuss the LTRs, and the knowledge gained from them, with the hope that by showing the distinctive narratives associated with each of these study sites, researchers will be inspired to use them to address their research questions and make sound predictions to facilitate the adaptation of Canadian agroecosystems to climate challenges. Through identifying the value generated by these unique LTRs, we hope that the importance of these sites will inspire not only their continued maintenance but also the next generation of LTRs.

Key words: long-term research, Canadian agriculture, soil health, tillage, amendment

Introduction

Soil health is the continued capacity of a soil to function as a vital living ecosystem for plants, animals, and humans (Norris et al. 2020). Soil health is therefore the foundation of environmental sustainability, whether in agricultural, grassland, forest, or wetland ecosystems. The difficulty is that soils are created, and continually evolve, due to the influences of climate, organisms, relief, parent material, and time (Jenny 1941) and more recently human activities (Richter and Yaalon 2012). Thus, Hole's song (1985) likened this dynamic diversity as "a rainbow of soil is under our feet" with red, black, yellow, white, and blue soils spread across the landscape. Each colour, or soil, will inherently have different properties and will support soil functions in different ways. For example, the dark black colour of a Chernozem's topsoil reflects its high organic matter content and grassland cover while the red colours of a Podzol reflect strong weathering under high levels of precipitation and coniferous forest cover (Canada Soil Survey Committee 1978). Therefore, what might be optimum soil health management practices for one soil may not be best for another. Thus, for practical purposes, here we will constrain ourselves to agricultural land management practices to improve soil health and agricultural sustainability.

Human activity—and management—has long had an imprint on soils in Canada and consequently on soil health. Landscapes in Canada that came to support contemporary agriculture were previously managed by Indigenous people for millennia—often with the intention of fostering food provisioning. Early colonizers of eastern Canada in the 1600s remarked on the sophistication and extensive impacts of Indigenous agriculture on the landscape (Riley 2002). Cultivating the three sisters (corn, beans, and squash grown together exploiting mutualistic benefits to all three) was among the practices documented by Europeans (Riley 2002). Ironically, this Indigenous management practice of intercropping that nurtures biological relationships is increasingly being explored as a contemporary soil health practice (Glaze-Corcoran et al. 2020). The impact of Indigenous agriculture on the landscape was erased as Indigenous people were dispossessed of their land; the forest re-established where the three sisters were once sown, and all evidence of Indigenous ingenuity was removed (Riley 2002). Indeed, newcomers in the 1800s remarked that the land was unoccupied and wild, thereby creating the myth of empty unkempt lands needing tending and settlers in the new world (Riley 2002).

Confederation in 1867 joined the three British North American provinces into the Dominion of Canada and established the Parliament of Canada's House of Commons and Senate. Here we take the view that committee discussions in the Houses of Parliament reflect contemporary public and government topics of interest. Therefore, not long after the confederation, in 1884, the topic of promoting and encouraging Canada's agricultural industry was of great importance (Gigault 1884). Gigault's report viewed agriculture as central to national prosperity but the general lack of knowledge by practitioners hindered agricultural development; therefore, it recommended the establishment of a research program within the Dominion Department of Agriculture. The Saunders Report (1886) followed up with a proposed structure for an agricultural research program, which included research sites across different regions of the country, and shortly thereafter the research program was created by the Act Respecting Experimental Stations (1886). Many agricultural areas were covered in the research program and, for crops, it was initially focused on testing crop varieties for different conditions (Anstey 1986; Harris and Mueller 1997). A targeted regional program, the Prairie Farm Rehabilitation Act, passed in April 1935 to address drought and soil erosion issues on the prairies (Bill 1935; Marchildon 2009). However, there were no prior mentions of soil conservation in committee reports, and, instead, for about the next hundred years government committee research in agriculture remained focused on the expansion of agricultural lands and optimizing crop yields with scientific research playing a significant supporting role (McMaster 1923; Weir 1943; Anstey 1986; Solberg 1987).

Reviewing committee discussions illustrates there was a shift in the 1980s from agricultural production to now include the ideas of agricultural environmental sustainability. For example, the Senate studied soil degradation: two of its conclusions were that soil, water, and wildlife are linked and cannot be managed in isolation and that more research was needed on the causes and effects of soil degradation (Sparrow 1984). In 1992, the House noted sustainable agriculture included economic, social, and environmental stability and recommended sustainable agriculture as an important part of life in Canada (Brightwell 1992). This period also produced the well-cited Agriculture and Agri-Food Canada report "The health of our soils" (Acton and Gregorich 1995). Interest in sustainability continued where the importance of funding agricultural research for the public good and not necessarily profit was noted in 2002 (Hubbard 2002) and reinforced by an emphasis in 2007 on both fundamental and applied agricultural research (Bezan 2007). Due to interest in 2018 on climate change and soil conservation, the House Standing Committee on Agriculture and Agri-Food recommended funding environmental sustainability research (Finnigan 2018). Concurrently, the importance of soil organic matter for resiliency was recognized by the Senate Committee with recommendations for increased research in longer term adaptation and resilience in agriculture (Griffin 2018). These Parliament committee reports illustrate the change in national interest on agriculture from colonization to maximizing yields, to sustainability.

Each phase of the government's interest in agriculture came with its own research questions—from what could be grown on a particular soil, to how much fertilizer to add, to how to manage for more than just yield. These questions and more were answered by both federal and university researchers. Federally, Agriculture and Agri-Food Canada (AAFC) was founded in 1886, and from the outset, research was an important component of its mandate. Within 20 years, the department had established research farms across the country (Anstey 1986), and, with the farms and their visionary scientists, numerous long-term research (LTRs) experiments were also established (e.g., Hopkins and Barnes 1928). Initially, these studies aimed to assess the feasibility of agricultural production, but as time progressed, they were used to probe more fundamental questions of the plant and soil system. In conjunction with federal research, universities with strong agricultural colleges were also establishing research farms and long-term experiments, for example, the University of Alberta (Newton 1936), University of Manitoba (Poyser et al. 1957), and University of Guelph (Congreves et al. 2014). Not only did these initial LTRs set out to answer the agricultural questions of the day such as the best crop rotations for prairie provinces (Hopkins and Barnes 1928), they have continued to answer farmer's and government's evolving questions and concerns on agriculture (e.g., Lafond and Harker 2012).

Janzen (1995) and Prescott (2014) both eloquently introduce and describe the importance of LTRs; one from the perspective of an LTR (Janzen 1995) and the other from a scientist who conducted research across numerous LTRs (Prescott 2014). They both identify that not only did the LTRs answer initial questions, but with time, the sites answered many more unforeseen questions. Our approach to highlighting the importance of LTRs is to identify how they are important to our national interest. Through describing the public's changing views on agricultural land management via House and Senate discussions, from food production to environmental sustainability, we identify the role LTRs play in supporting our evolving national focus on soils and the challenge in anticipating future needs and research questions in agriculture. What is clear is how LTR experiments have proven to be a useful, and often an essential, tool for scientists addressing the public's needs—with their continued relevance readily identified in a recent soil health project (Norris et al. 2020).

The North American Project to Evaluate Soil Health Measurements (NAPESHM) project was a continental-scale effort to evaluate effective measurements for soil health (Norris et al. 2020). Detecting effects of management practices on soil conditions can be challenging due to a lack of consensus or knowledge on the appropriateness and approaches to soil health measurements; NAPESHM set out to address this knowledge gap. Seventeen Canadian federal and university LTRs were included in the project with some LTRs co-located at the same site (Fig. 1). Results from this project are now being published in aggregate from sites spanning from Mexico to Canada (Bagnall et al. 2022; Liptzin et al. 2022; Rieke et al. 2022). We recognize there are other LTRs in Canada, but our objectives here are to use the NAPESHM sites in Canada to illustrate how LTRs are important to our national interest through (*i*) highlighting the breadth and depth of knowledge gained previously from the sites, (*ii*) illustrating the diversity of soils sampled and to provide a foundational background for future analysis, and (*iii*) discussing how these and other LTRs can continue to address future questions of stakeholders including governments, land managers, and society.

Material and methods

The long-term experiments were chosen to be in NAPESHM if their design included physical disturbance (e.g., tillage or grazing treatments), differences in crop rotation or diversity, organic amendments (e.g., manures or composts), cover crops, or water management (Norris et al. 2020). Furthermore, experiments could only be included if they had long-term management data (i.e., >10 years). Seventeen of the 120 LTRs chosen for NAPESHM are in Canada and are located in Alberta through Ontario (Fig. 1). Soils were collected from April—June 2019 and occurred prior to spring management activity at all sites. To constrain costs and time, not all treatments or phases were sampled; however, those treatments sampled are identified within the LTRs' respective table (Tables 1–8). If multiple crop phases were present at a site, where possible, the phase being sown to the first cash crop (as opposed to perennials or fallow) was sampled. For example, if an experiment that contained both fallow-wheat (FW) or F-W-W rotations, the plot (i.e., the experimental unit) selected was fallow in 2018 and soil sampling occurred prior to wheat planting in 2019 while for a rotation of wheat-oat-barley-hay-hay (WOBHH), the plot sampled was hay in 2018 and wheat in 2019.

Depending on plot size, either four or six 15 × 15 cm holes were made, soil was collected to a depth of 15 cm aseptically from three of the four sides of the hole, and all soil was composited. Soils were homogenized with an 8-mm sieve, split for subsamples, and always kept cool prior to sending to the analytical laboratories. A suite of 29 soil analyses including soil physical, soil chemical, and soil biological tests along with measurements from three existing soil health evaluation programs were performed on each sample (Norris et al. 2020). On this project, the same laboratory analyzed all soil samples for a specific measurement. For example, all particle size, pH, and organic carbon concentration, and determinations were conducted by the Soil Water and Environmental Lab at Ohio State University (Gee and Bauder 1986; Nelson and Sommers 1996; Thomas 1996; Sikora and Moore 2014). Data processing and visualization were performed with R version 3.5.0 (R Development Core Team) using RStudio. Percent soil clay, soil pH, and soil organic carbon data are presented in histograms with all the Canadian sites included. Mean site values for NAPESHM soil pH and soil texture were used (0–15 cm) for reporting site characteristics (Tables 1–8). NAPESHM data are available for analysis through the Soil Health Institute or individual site investigators.

Results

The NAPESHM Canadian soil data

The LTRs in this project covered a range of soil properties (Fig. 2). The Ridgetown study had the lowest clay content (<5%), while Indian Head and Glenlea had >40% clay. Most sites had a clay content between 10% and 30%. Soil pH between 6.5 and 8 was the most common. There was one very low pH (3.95) measured for Breton's WOBHH NPKS plot, which was in contrast to two Erosion plots, and seven plots from Indian Head, which were at pH 8 or greater. Soil organic carbon also had a wide range of values from 1% to 10%. The plot for Breton's WF check was the lowest concentration with 0.7%, while some plots for Long-Term Manure and Stavely exceeded 5%.

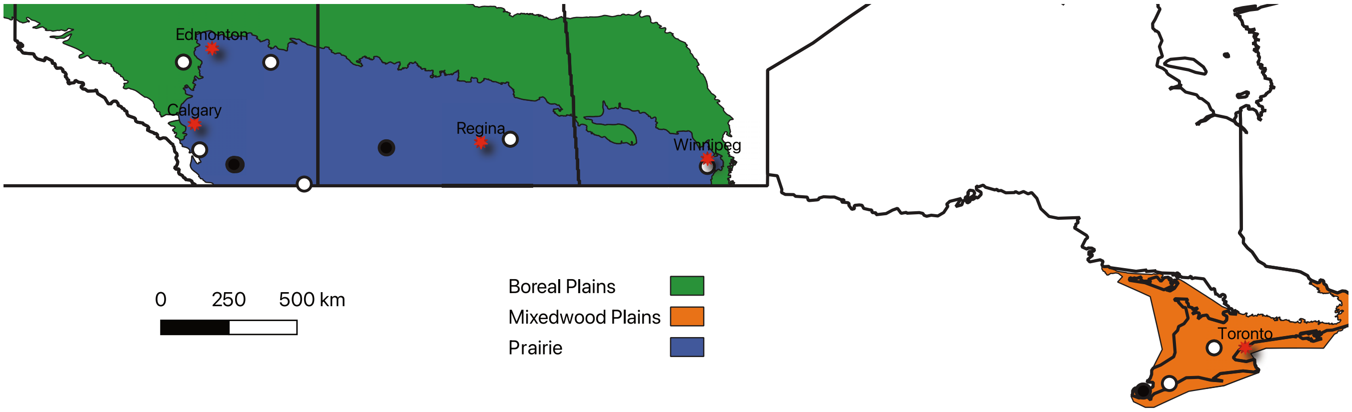
Long-term research sites

The Breton plots

The Breton Classical Plots were established in 1929, and the Breton Hendrigan Plots were established in 1980 (Dyck et al. 2012). These two LTRs are co-located on Gray Luvisols southwest of Edmonton, Alberta, on a site called the Breton Plots and have been continuously managed by the University of Alberta. The Breton Classical Plots were created to better understand crop rotations and fertilizers to improve agricultural production on Gray Wooded soils. The Classical Plots consist of two crop rotations, fallow-wheat (FW) and wheat-oat-barley-hay-hay (WOBHH), to test eight different nutrient regimes (Table 1). The Hendrigan plots include three crop rotations: two extremes of continuous grain and continuous forage, and an 8-year rotation that is meant to be self-sufficient for nitrogen.

Shortly after implementation, the Breton Classical Plots identified sulphur deficiencies in the gray-wooded soils (Newton 1936), and by 1939 fertilizer rates were published for wheat production on these soils (Wyatt et al. 1939). The effects of fertilizer management and rotation on soil nutrient stocks and crop yield have since become very apparent when comparing wheat yields of the FW and WOBHH rotations of the Classical Plots (Dyck and Puurveen 2020). Greater overall grain and biomass removals in the WOBHH rotation have decreased soil P, K, and S stocks to a greater extent than in the FW rotation, but the decrease in soil N stocks is offset by biological fixation from alfalfa and clover in the WOBHH rotation. The unique nutrient balances in the WOBHH and FW rotations have resulted in varied responses of wheat yields

Fig. 1. Map illustrating the geographic location of the 17 Canadian long-term research experiments (LTRs) that were part of the North American Project to Evaluate Soil Health Measurements. Locations with one experiment are indicated by empty circles, and those with multiple LTRs are indicated by filled-in circles. Different colours indicate different ecozones that the LTRs are located within. The map is in WGS84 EPSG:4326 with data from Open Government Cartographic Boundary File (https://open.canada.ca/data/en/data set/a883eb14-0c0e-45c4-b8c4-b54c4a819edb) and from the Nation Soil Database (https://sis.agr.gc.ca/cansis/nsdb/ecostrat/gis_data.html).



to applied nutrients with respect to rotation. In the WOBHH rotation, wheat yields increased with applied N, P, S, and K, and the increase in wheat yields from applied S and P is similar. In contrast, wheat yields in the FW rotation increased with applied N, P, and S (but not K), and the increase in wheat yield from applied N and P was much greater but much lower for applied S than in the WOBHH rotation. Lime additions to maintain pH at or above 6.0 have benefited alfalfa establishment, alfalfa-brome yields, but not cereal yields (Dyck et al. 2012).

Overall, rotation and fertilization have driven C and N balances in the Luvisolic soils at the Breton Plots (Grant et al. 2001, 2020; Izaurralde et al. 2001; Ross et al. 2008; Giweta et al. 2014, 2016; Dyck and Puurveen 2020; Sorenson et al. 2020). Rotations including perennial forages have accrued soil C in the top 15 cm since they were established with applied nutrients and manure also significantly influencing the C balance of all rotations (Grant et al. 2001, 2020; Izaurralde et al. 2001; Ross et al. 2008; Giweta et al. 2014; Sorenson et al. 2020). In addition, crop productivity, nutrient balances, and response to applied nutrients were a function of the crop rotation.

Roy Berg Kinsella Research Ranch

The Roy Berg Kinsella Ranch was established in 1960 in the Aspen Parkland, about 150 km southeast of Edmonton, by the University of Alberta as a beef cattle breeding facility, and it continues to be a site of cattle research today. Kinsella is on Treaty 6, the traditional territories of the Očhéthi Šakówiŋ (Sioux), Cree, Michif Piyii (Métis), and Niitsítpiis-stahkoii ᖹᐟᒧᐧᒣᑯᐧ ᓴᐦᖾᐟ (Blackfoot/Niitsítapi ᖹᐟᒧᐧᒣᑯ) First Nations. The gently rolling parkland topography of Kinsella is dominated by Orthic Black Chernozemic soils (Naeth et al. 1990). In addition to cattle breeding research (e.g., Akanno et al. 2015), the 5000-ha site has provided the opportunity for research in rangeland and plant ecology, including studies of climate and grazing effects on rough fescue plant communities (White et al. 2014), herbivore effects on aspen (Bork et al. 2013), the role of plant litter in regulating soil moisture (Deutsh et al. 2010), and seed bank dynamics (Brown and Cahill 2020), to name a few. In particular, past research has identified that high-intensity grazing reduced soil organic matter (Naeth et al. 1991*a*), increased bulk density (Naeth et al. 1990), and reduced soil water (Naeth et al. 1991*b*) compared to light grazing.

The Roy Berg Kinsella Research Ranch has provided the opportunity to maintain long-term field treatments, including long-term cattle exclosures. Exclosures have commonly been used in rangeland science to investigate the effects of grazing on grassland ecosystems. The exclosures used in NAPESHM were constructed by Art Bailey in 1979 for the purposes of studying the seasonality of cattle grazing on aspen recruitment following controlled burns (Fitzgerald and Bailey 1984). Since the 1980s, grazing outside of the exclosures has been light to moderate, and in the early 2000s the area surrounding a subset of the exclosures was reduced to extremely light grazing with no grazing happening in most years.

Kinsella's exclosures are similar to those maintained by the province of Alberta as part of the Rangeland Reference Area (RRA) program (e.g., Adams et al. 2013). This program has enabled significant research into understanding grassland ecosystem functions such as grazing effects on plant community composition (Lyseng et al. 2018), the sensitivity of plant biomass production to rainfall (Batbaatar et al. 2021), soil carbon content (Hewins et al. 2018), and the underlying mechanisms through which grazing alters the plant community to affect soil carbon (Bork et al. 2019). The network of RRAs highlights the benefits of long-term spatially replicated networks for understanding broad patterns of agroecosystem responses to land management.

Table 1. Breton Long-Term Rotation site and experimental details.

Site details			
Location	University of Alberta, Breton Plots		
Treaty Territory	Treaty 6 (1876), and the traditional territories of the Sioux, Cree, Blackfoot, and Métis First Nations.		
Mean annual temperature (C)	3.1		
Mean annual precipitation (mm)	606		
Soil type	Gray Luvisol and Dark Gray Luvisol		
Soil texture	Loam		
pH	5.3		
LTR details			
Name	**Breton Classical Plots**		Treatments
Soil health management	Crop Rotation, Amendment	WF	Wheat–fallow
System	Wheat	WOBHH	Wheat–oats–barley–hay–hay
Year established	1929	1	Control
Design	Two crop rotations with 8 treatments each	2	Manure
Replication	1	3	NPKS fertilizer
Plot size	8.5 m × 30 m	4	NSK fertilizer (no P)
Notes:	pH measured every 5 years since 1972	5	Control
	if < 6.0 pH, then lime added for pH 6.5 on the East half of WOBHH plots and all of WF	6	Lime
		7	NPK fertilizer (no S)
	Average marketable crop yields (2000–2019): WF (NPKS) 1.04, WOBHH (NPKS) 1.38	8	PKS fertilizer (no N)
		9	NPKS fertilizer
	Wheat—*Triticum aestivum* L.	10	NPS fertilizer (no K)
	Oat—*Avena sativa* L.	11	Control
	Barley—*Hordeum vulgare* L.	*	**WF2, WF3, WF5, WOBHH2, WOBHH3, WOBHH5 (NAPESHM sampled)**
	Hay—alfalfa (*Medicago sativa*) and brome (*Bromus tectorum*)		
Name	**Hendrigan Plots**		Treatments
Soil health management	Crop rotation	**CG**	Continuous grain
System	Wheat	**CF**	Continuous forage
Year established	1980	**8 year agro eco**	Barley—barley—faba—barley—barley—hay—hay—hay
Design	Unbalanced CRD		
Replication	1		
Plot size	8.5 m x 30 m		
Notes:	Average marketable crop yields (2000–2019): CG 1.14, CF 1.0, 8-year 1.35		
	CG—barley (*Hordeum vulgare* L.)		
	CF—creeping red fescue (*Festuca rubra*), tall fescue (*Festuca arundinacea*), white "Dutch" clover (*Trifolium repens*)		
	Faba beans—*Vicia faba*		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

Stavely Research Ranch

Stavely Research Ranch was established in 1949, about 100 km south of Calgary, by Agriculture and Agri-Food Canada (AAFC) Lethbridge Research and Development Centre (Douwes and Willms 2012). The LTR is on Treaty 7, the traditional territories of the Siksika (Blackfoot), Kainai (Blood), Piikani (Peigan), Stoney-Nakoda, and the Tsuut'ina (Sarcee) First Nations. Stavely was established to study the effects of various long-term cattle stocking rates on the Orthic Black Chernozems of the native fescue prairie of Alberta's foothills. Across its history, Stavely has been used as a site for multiple rangeland studies including soil, vegetation, and livestock research. While unreplicated, Stavely's core 1949 treatments of exclosures, 1.2 AUM/ha (light grazing), 2.4 AUM/ha (heavy

Table 2. Lethbridge Long-Term Rotation site and experimental details.

Site details			
Location	Agriculture and Agri-Food Canada, Lethbridge Research and Development Centre		
Treaty Territory	Treaty 7 (1877), traditional territory of the Blackfoot Confederacy comprising the Kainai, Piikani, Amskapiipikani, and Siksika First Nations		
Mean annual temperature (C)	5.8		
Mean annual precipitation (mm)	371		
Soil type	Dark Brown Chernozem		
Soil texture	Loam		
pH	7.4		
LTR details			
Name	**Dryland Rotation120**	Treatments	
Soil health management	Crop rotation, amendment	**CW**	Continuous wheat; no fertilizer
System	Wheat	**CW + F**	Continuous wheat; with fertilizer
Year established	1951	FW	Fallow—wheat; no fertilizer
Design	Random complete block	FW + F	Fallow—wheat; with fertilizer
Replication	4	FWW	Fallow—wheat—wheat; no fertilizer
Plot size	36.6 m × 3.2 m	FWW + F	Fallow—wheat—wheat; with fertilizer
Notes:	1985 fertilizer, green manure, and native grass treatments added	**OpmWW**	Oat pea manure—wheat—wheat; no fertilizer
		GmWW	Green manure—wheat—wheat; no fertilizer
	1995–2000 entire LTR cropped to spring wheat	FmWW	Fallow manure—wheat—wheat; no fertilizer
	2001 re-establish original 5, 5 from 1985, and 3 new treatments (OpmWW, M + F, H)	FWWHHH	Fallow—wheat—wheat—hay—hay—hay; no fertilizer
		M + F	Corn maize + fertilizer
	Wheat—*Triticum aestivum* L.	H	Hay
	Oat—*Avena sativa* L.	**NG**	Native grass
	Pea—*Pisum sativum*		
	Green manure—*Lens culinaris* cv. Indian Head		
	Hay—crested wheat grass (*Agropyron cristatum* L.) and alfalfa (*Medicago sativa*)		
	Native grass mixture—blue gama (*Bouteloua gracilis* (Willd. Ex Kunth) Lag. ex Griffiths); June grass (*Koeleria macrantha* (Ledeb.) Schult.); green needle grass (*Nassella viridula* (Trin.) Barkworth); needle and thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth); western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve)		
Name	**Long-Term Manure**	Treatments	
Soil health management	Amendment	**Mr0**	Continuous rainfed; 0 manure
System	Continuous barley	**Mr30**	Continuous rainfed; 30 manure
Year established	1973	**Mr60**	Continuous rainfed; 60 manure
Design	Random complete block	Mr90	Continuous rainfed; 90 manure
Replication	3	**DDr30**	2003 rainfed; 30 manure
Plot size	7.62 × 15.24 m or 3.81 m × 15.24 m	**DDr60**	2003 rainfed; 60 manure
Notes:	Manure added as tonnes ha^{-1} wet weight	DDr90	2003 rainfed; 90 manure
	tillage treatments of plow, rototill, and cultivator	**Mi0**	Continuous irrigated; 0 manure
	1987 onwards manure incorporated only with cultivator	**Mi60**	Continuous irrigated; 60 manure
	2003 manure application ceased on previously plowed strip (DDr and DDi)	**Mi120**	Continuous irrigated; 120 manure
		Mi180	Continuous irrigated; 180 manure
	Barley—*Hordeum vulgare* L.	**DDi60**	2003 irrigated; 60 manure

Table 2. (*concluded*).

Site details			
		DDi120	2003 irrigated; 120 manure
		DDi180	2003 irrigated; 180 manure
Name	**Artificial Erosion Dryland and Irrigated**		Treatments
Soil health management	Crop rotation, amendment	0	No topsoil removed
System	Continuous wheat	5	5 cm topsoil removed
Year established	1990	10	10 cm topsoil removed
Design	Random complete block	15	15 cm topsoil removed
Replication	4	20	20 cm topsoil removed
Plot size	3 m × 10 m	C	Check; no amendment
Notes:	Amendment subtreatments superimposed on erosion cuts	F	Fertilizer; optimum of 75 kg ha^{-1} N, 22 kg ha^{-1} P
	Manure (0.35 kg kg-1 water content), containing 190 g kg-1 C and 22 g kg-1 N, dry wt	T	Topsoil; re-application of 5 cm topsoil
		M	Manure; 75 Mg ha^{-1} (wet wt) of beef feedlot manure
	Fertilized annually with N and P at recommended rates	*	**0C, 10C, 20C, 0M, 10M, 20M (NAPESHM sampled)**
	2004 entire LTR chemical fallow to control weeds		
	Irrigated- 100–200 mm water during growing season		
	Wheat—*Triticum aestivum* L.		
Name	**Cquest**		Treatments
Soil health management	Crop rotation, amendment	**CW**	Continuous wheat; no N fertilizer
System	Wheat	**CW + F**	Continuous wheat; with N fertilizer
Year established	1993	**FW**	Fallow—wheat; no N fertilizer
Design	Completely randomized design	**FW + F**	Fallow—wheat; with N fertilizer
Replication	4	**CWG**	Crested wheatgrass; no N fertilizer
Plot size	5.6 m × 160 m	**CWG + F**	Crested wheatgrass; with N fertilizer
Notes:	1993 baseline soil samples from 0–15, 15–30, 30–60, 60–90, and 90–120 cm	**NG**	Native grass; no N fertilizer
		NG + F	Native grass; with N fertilizer
	1995 fertilizer N split		
	Soil samples collected in 1999, 2005, and 2015		
	Wheat—*Triticum aestivum* L.		
	Crested wheatgrass—*Agropyron cristatum* L.		
	Native grass mixture—blue grama (*Bouteloua gracilis* (Willd. Ex Kunth) Lag. ex Griffiths); June grass (*Koeleria macrantha* (Ledeb.) Schult.); green needle grass (*Nassella viridula* (Trin.) Barkworth); needle and thread grass (*Hesperostipa comata* (Trin. & Rupr.) Barkworth); western wheatgrass (*Pascopyrum smithii* (Rydb.) A. Löve)		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

grazing), and 4.8 AUM/ha (very heavy grazing) continue to be maintained by Alberta's Provincial government. In addition, three exclosures were constructed in 1998 within each of the 2.4 and 4.8 AUM/ha fields. Each exclosure was paired with an adjacent plot outside to provide a continuous grazing treatment. These exclosures have been monitored to measure the recovery of the vegetation and soil within these overgrazed pastures. Stavely also supports an Alberta Public Lands RRA benchmark site.

Results from Stavely consistently report on the negative effects of heavy long-term stocking rates. This includes soil erosion which was 76 times greater after 10 years of very heavy grazing pressure when compared to heavy grazing (Johnston 1961). Another study showed that very heavy grazing had altered the Ah horizon color from black to dark brown and decreased organic matter (Johnston et al. 1971). Following over four decades of very heavy and heavy grazed areas, research showed a reduction in the depth of the Ah, a bulk density increase, higher pH, and a decrease in the C/N ratio when compared to the lightly and ungrazed fields (Dormaar and Willms 1998). In a more recent assessment of soil C and N stocks, the effects of grazing intensity were undetectable (C. Li et

Table 3. Swift Current Long-Term Rotation site and experimental details.

Site details			
Location	Agriculture and Agri-Food Canada, Swift Current Research and Development Centre		
Treaty Territory	Treaty 4 (1874), and the traditional territories of the Cree, Saulteaux, and Assiniboine First Nations		
Mean annual temperature (C)	3.9		
Mean annual precipitation (mm)	387		
Soil type	Orthic Brown Chernozem		
Soil texture	Loam		
pH	5.2		
LTR details			
Name	**0MC**		Treatments
Soil Health Management	Tillage, Crop Rotation	**CW NT**	Continuous wheat; no till
System	Wheat	CW MT	Continuous wheat; minimum till
Year established	1981	**FW NT**	Fallow—wheat; no till
Design	Random complete block	FW MT	Fallow—wheat; minimum till
Replication	4	**FW CT**	Fallow—wheat; conventional till
Plot size	15 m × 76 m	**PW NT**	Pulse—wheat; no till
Notes:	Pre-1996 N fertilizer split between seed-placed and broadcast	**PW CT**	Pulse—wheat; conventional till
		GmW RT	Green manure—wheat; reduced till (organic system)
	Post-1996 N fertilizer banded 2–3 cm below and to the side of seeds	GmW CT	Green manure—wheat; conventional till (organic system)
	Phosphorus applied with seed		
	1997 PW treatments added		
	2006 GmW treatments added		
	Wheat—*Triticum aestivum*		
	Pulse crops vary among chickpea (*Cicer arietinum*), field Pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medikus)		
Name	**New Rotation**		Treatments
Soil health management	Crop rotation	**CW**	Continuous wheat
System	Wheat	FWW	Fallow—wheat—wheat
Year established	1987	FW(hy)W(hy)	Fallow—wheat hybrid—wheat hybrid
Design	Random complete block	**GmWW**	Green manure—wheat—wheat
Replication	3×	FWWW	Fallow—wheat—wheat—wheat
Plot size	15 m × 45 m	**WCWP**	Wheat—canola—wheat—pea
Notes:	No-till except green manure incorporation	**CWG**	Crested wheat grass
	2003 two original rotations were discontinued and plots were randomly assigned to new WCWP		
	2016 CWG modified to mixed CWG and meadow brome		
	2016 FW(hy)W(hy) modified to F-durum wheat-durum wheat		
	Wheat—*Triticum aestivum*		
	Green manure lentil—*Lens culinaris* Medik		
	W(hy)—high-yielding CPS wheat		
	Canola—*Brassica napus* L.		
	Field pea—*Pisum sativum* L.		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

al. 2012), but when the slope was considered labile soil organic matter (Zhang et al. 2018*a*) and soil C and N stocks were affected by grazing intensity (Zhang et al. 2018*b*). In summary, Stavely has identified for the fescue prairie foothills that while light grazing does not affect range condition, anything more intense can degrade the rangeland (Douwes and Willms 2012).

Other research at Stavely includes a study which highlighted that soil and litter N was less water-extractable at high grazing intensities which may have been due to the quality of the litter input (Dormaar and Willms 1992). However, Y. Zhang et al. (2019 - unpublished) found that while soil physical properties improved on overgrazed pastures following 20 years of livestock exclusion, soil C and N content had not sig-

Table 4. Indian Head Long-Term Rotation site and experimental details.

Site details			
Location	Indian Head Research Farm		
Treaty Territory	Treaty 4 (1874), and the traditional territories of the Cree, Saulteaux, and Assiniboine First Nations		
Mean annual temperature (C)	3.0		
Mean annual precipitation (mm)	435		
Soil type	Rego Black Chernozem		
Soil texture	Clay		
pH	7.9		
LTR details			
Name	**Indian Head**	Treatments	
Soil health management	Crop rotation	**CW**	Continuous wheat; no fertilizer
System	Wheat	**CW + F**	Continuous wheat; with fertilizer
Year established	1957	FW	Fallow—wheat; no fertilizer
Design	Randomized complete block	FW + F	Fallow—wheat; with fertilizer
Replication	4	FWW	Fallow—wheat—wheat; no fertilizer
Plot size	4.6 m × 33.5 m	**FWW + F**	Fallow—wheat—wheat; with fertilizer
Notes:	1978 changed from recommended fertilizer rate to be based on soil tests	FWW + F—S	Fallow—wheat—wheat; with fertilizer; straw removed
		GmWW	Green manure—wheat—wheat; no fertilizer
	1990 converted to no-till	**FWWHHH**	Fallow—wheat—wheat—hay—hay—hay; no fertilizer
	Wheat—*Triticum aestivum* L.		
	Green manure—black lentil (*Vigna mungo*)		
	Hay—alfalfa (*Medicago sativa*)		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

nificantly improved when compared to heavily grazed areas. Y. Zhang et al. (2020) also looked at the soil bacterial composition within the grazing treatments and that while moderate grazing had no effect on soil bacterial composition, the evenness and diversity indices decreased with 64 years of heavy grazing when compared to the non-grazing treatment.

Lethbridge Dryland Rotation 120

The study now called "Rotation 120" was originally established in 1951 at the AAFC Lethbridge Research and Development Centre in southern Alberta on a Dark Brown Chernozem (Pittman 1977). Initially, the study was called "Rotation 96" because it included 96 plots, and during its 70-year history the number of plots has expanded to 120 as some treatments were discontinued while others were added. Five of the original seven rotations have been maintained continuously since 1951 with only minimal disruption. These included mainly spring wheat and summer-fallow, but also winter wheat and perennial hay crops were grown for 3 consecutive years in rotation with wheat and fallow (Table 2). The book chapter by Janzen et al. (1997) provides a summary of the experiment, including crop yield data. The earlier work focussed on agronomy and best management practices. Initially, the focus was on summer fallow frequency and integrated production of perennial forages with annual crops; subsequently, the focus shifted to nitrogen fertility and greater use of legumes. Major modifications were introduced in 1985 and again in 2001, and these are detailed in Smith et al. (2012).

During the 6-year period from 1995 through 2000, the entire experimental area was cropped to spring wheat, so that productivity under uniform cropping could be used as a bioassay to assess changes in soil health that had accumulated since the experiment was started in 1951. The wheat bioassay years indicated that prior cropping systems strongly influenced subsequent productivity and soil organic matter properties. The former systems with legumes or with fertilizer N out-performed those with frequent summer fallow, and soil N cycling influenced both productivity and crop quality (Smith et al. 2015).

In 2001, most of the cropping systems were re-established, including the five originally initiated in 1951, five of the eight introduced in 1985 or earlier, and three new systems. Since N availability is so crucial for maintaining productivity, the experiment will enable comparisons among a variety of N inputs including atmospheric deposition alone, livestock manure, industrially fixed fertilizer N, and biologically fixed N in legumes grown as green manure, annual forage (intercropped with oats), and perennial alfalfa (intercropped with grass). Many of the sources have distinct ^{15}N natural abundances that are proving useful to discern plant N supplies,

Table 5. Glenlea Long-Term Rotation site and experimental details.

Site details			
Location	University of Manitoba		
Treaty Territory	Treaty 1 (1871) and traditional homelands of the Métis nation		
Mean annual temperature (C)	3.8		
Mean annual precipitation (mm)	580		
Soil type	Rego Black Chernozem		
Soil texture	Clay		
pH	7.0		
LTR details			
Name	**Glenlea Long-Term Rotation**		Treatments
Soil health management	Crop rotation, amendment	**FGO**	Wheat—flax—alfalfa—alfalfa; Organic
System	Wheat	**FGO + compost**	Wheat—flax—alfalfa—alfalfa; organic + compost manure
Year established	1992	**FGC**	Wheat—flax—alfalfa—alfalfa; Conventional
Design	Complete randomized design	**GGO**	Soybean—wheat—flax—oat; Organic
Replication	3	**GGC**	Soybean—wheat—flax—oat; Conventional
Plot size	4 m × 28 m	**prairie**	Prairie—no graze and no cut with burn/5 years
Notes:	1 acre prairie plots		
	Forages are cut twice per year and removed		
	Tillage regimes similar between conventional and organic		
	2004 became fully phased		
	2007 FGO manure split		
	Wheat—*Triticum aestivum* L.		
	Legume—pea (*Pisum sativum* L.) or hairy vetch (*Vicia Villosa*) after 2014		
	Barley—*Hordeum vulgare* L.		
	Flax—*Linum usitatissimum* L.		
	Oat—*Avena sativa* L.		
	Soybean—*Glycine max* L.		
	Forage mixture—alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), orchardgrass (*Dactylis glomerata* L.), and timothy (*Phleum pratense* L.)		
	Prairie mixture—northern wheatgrass (*Elymus lanceolatus* (Scribn. and J.G. Sm.) Gould ex Shinners), slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners), western wheatgrass (*Pascopyrum smithii* (Rydb.), Indian grass (*Sorghastrum nutans* (L.) Nash), switchgrass (*Panicum virgatum* L.), and big bluestem (*Andropogon gerardii* Vitman)		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

and the systems with forage or livestock manure will afford opportunities to explore integrated crop-livestock systems in the future. The experiment has provided rich insight into the biogeochemistry of long-term C and N cycling, aided by the use of ^{14}C, ^{13}C, and ^{15}N isotopes (Ellert and Janzen 2006).

Lethbridge Long-Term Manure

The Long-term Manure Plot was established in the fall of 1973 on a Dark Brown Chernozem at the AAFC Lethbridge Research and Development Centre (Hao and Benke 2012). The Long-Term Manure plots were created to determine the maximum safe loading rate for cattle feedlot manure on local soils under barley forage production, with the first decade also focusing on soil properties and groundwater quality. In later years (from 1987 on), the residual effects of the long-term manure applications were also investigated.

The beef cattle feedlot manure application rates were 0, 30, 60, and 90 tonnes ha^{-1}, wet weight, for the rainfed field and 0, 60, 120, and 180 tonnes ha^{-1} for the irrigated field (Table 2). These application rates corresponded to one, two, and three times the recommended rates for rainfed and irrigated crop production for the soil type at the site (Alberta Agriculture 1980). To compare methods of incorporating manure into the soil, three tillage treatments (plow, rototill, and cultivator plus disc) were used. Since tillage had no discernible effect on most soil properties investigated (Sommerfeldt and

Table 6. Elora Long-Term Rotation site and experimental details.

Site details			
Location	University of Guelph, Elora Research Station		
Treaty Territory	Simcoe Patent (Ontario Treaty 4, 1793), traditional territories of the Mohawk, Seneca, Oneida, Cayuga, Onondaga, and Tuscarora First Nations		
Mean annual temperature (C)	7.2		
Mean annual precipitation (mm)	1024		
Soil type	Gray Brown Luvisol		
Soil texture	silt loam		
pH	7.6		
LTR details			
Name	**Elora**	Treatments	
Soil health management	Tillage, Crop Rotation	**CCCC NT**	Continuous corn; no till
System	Corn	**CCCC CT**	Continuous corn; conventional till
Year established	1980	CCOB NT	Corn—corn—oat—barley; no till
Design	Randomized complete block	CCOB CT	Corn—corn—oat—barley; conventional till
Replication	4	CCOrcBrc NT	Corn—corn—oat/red clover—barley (underseeded red clover); no till
Plot size	6.1 m × 16.7 m	CCOrcBrc CT	Corn—corn—oat/red clover—barley (underseeded red clover); conventional till
Notes:	2000 CCOB was switched from CCBB and CCOrcBrc was switched from CCBrcBrc	**CCSS NT**	Corn—corn—soybean—soybean; no till
		CCSS CT	Corn—corn—soybean—soybean; conventional till
		CCSWW NT	Corn—corn—soybean—winter wheat; no till
	2002 tillage switched from conservation to no-till	**CCSWW CT**	Corn—corn—soybean—winter wheat; conventional till
		CCSWWrc NT	Corn—corn—soybean—winter wheat (underseeded red clover); no till
	Corn—*Zea mays* L.	**CCSWWrc CT**	Corn—corn—soybean—winter wheat (underseeded red clover); conventional till
	Soybean—*Glycine max* L.	**CCAA NT**	Corn—corn—alfalfa—alfalfa; no till
	Alfalfa—*Medicago sativa* L.	**CCAA CT**	Corn—corn—alfalfa—alfalfa; conventional till
	Oat—*Avena sativa* L.	AAAA CT	Alfalfa—alfalfa—alfalfa—alfalfa
	Barley—*Hordeum vulgare* L.		
	Winter wheat—*Triticum aestivum*		
	Red clover—*Trifolium pratense* L.		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

Chang 1985; Sommerfeldt et al. 1988), from 1987 manure was incorporated with a cultivator for all plots. Manure applications were ceased for the previously rototilled strip after 14 annual applications. Then in 2003, manure application ceased for the previously plowed strip after 30 annual applications.

The long-term manure applications at all rates increased organic matter, N, P, salt, and trace minerals levels in soil. The straw yield at all manure rates increased, but grain yields at higher application rates were reduced. Increased nutrient levels in soil also increase the potential for nutrient losses and surface and groundwater contamination. The soil enrichments were long-lasting and could pose environmental threats long after application has ceased (Indraratne et al. 2009; Benke et al. 2013).

Lethbridge Artificial Erosion dryland and irrigated

Only two sites remain (Lethbridge Dryland, Lethbridge Irrigated) from a larger soil erosion-productivity study initiated at six sites in 1990–1991 (Larney and Janzen 2012). The two sites were artificially eroded in spring 1990 and are located 5.5 km apart on Dark Brown Chernozems at AAFC Lethbridge Research and Development Centre. The study design for both Dryland and Irrigated LTR is described in detail by Larney et al. (2000*a*, 2000*b*). Briefly, five topsoil re-

Table 7. Ridgetown Long-Term Rotation site and experimental details.

Site details			
Location	Ontario Crops Research Centre—Ridgetown		
Treaty Territory	McKee Purchase (Ontario Treaty 2, 1790), and the traditional territory of the Ojibwa, Odawa, and Potawatomi		
Mean annual temperature (C)	9.3		
Mean annual precipitation (mm)	942.4		
Soil type	Orthic Humic Gleysol		
Soil texture	Loamy Sand		
pH	6.6		
LTR details			
Name	**Ridgetown Long-Term Cover Crop Experiment**	Treatments	
Soil health management	Cover crop	control − R	No cover, residue removed
System	Processing vegetable- grain rotation	**control + R**	No cover, residue remains
Year established	2007, 2008	oat − R	Oat, residue removed
Design	Split-plot (covers arranged as random complete block)	oat + R	Oat, residue remains
Replication	4	rye − R	Cereal fall rye, residue removed
Plot size	16 m x 6 m	**rye + R**	Cereal fall rye, residue remains
Notes:	Residue removal with some crops (winter wheat + initially grain corn)	rad − R	Radish, residue removed
		rad + R	Radish, residue remains
	Split plot: 8 m × 6 m	rad + rye -R	Radish with rye mix, residue removed
	Oat—*Avena sativa* L.	**rad + rye + R**	Radish with rye mix, residue remains
	Rye—*Secale cereale* L.		
	Oil seed radish—*Raphanus sativus* L. var. oleiferus Metzg Stokes		

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

moval treatments (12 m × 10 m main plots) were established by mechanically removing 0, 5, 10, 15, or 20 cm of topsoil (referred to as cuts) using an excavator with a grading bucket (Table 2). Four amendment sub-treatments were super-imposed on each of the main cut treatments as follows: (1) check: no amendment; (2) fertilizer: an optimum rate of N and P; (3) manure: 75 Mg ha^{-1} (wet wt.) of beef feedlot manure; and (4) topsoil: re-application of 5 cm of topsoil. Subsequently, sites were seeded to spring wheat annually, and, therefore, any differences in productivity are due to legacy effects of one-time treatments applied at the outset in 1990.

Erosion, but not amendment, effects in the initial year at all six sites were reported by Larney et al. (1995). Early (first 2–3 years) effects on soil (Larney et al. 2000a) and crop (Larney et al. 2000b) responses were reported for the four southern Alberta sites. Subsequently, over 16 year (1990–2006), average grain yield reductions at the two sites were 10% for 5 cm, 20% for 10 cm, 29% for 15 cm, and 39% for 20 cm of topsoil removal compared to check plots with no amendment (Larney et al. 2009). Moreover, there was also evidence that restoration of grain yield levelled off at a value less than the non-eroded treatment (0-cm cut). The amendments ranked manure > topsoil > fertilizer in terms of restoring productivity to the desurfaced soils.

Assessing soils from the Lethbridge Dryland site only, Larney et al. (2016) reported that in the absence of amendments, light fraction C (C_{LF}) and mineralizable C (C_{min}) recovered sufficiently by 2004 to render the cut effect non-significant. Soil organic C (SOC) responded more slowly, with the 10-cm cut recovering to the 0-cm cut concentration by 2004, and the 20-cm cut (13.9 g kg^{-1}) remaining significantly lower than the 0-cm cut (16.3 g kg^{-1}) through to 2012. Nitrogen fractions behaved similarly. Across cuts and years (2004, 2012), C fraction values were 19%–27% greater on the manure vs. check sub-treatment (17.5 vs. 14.7 g kg^{-1} for SOC, 1.38 vs. 1.09 g kg^{-1} for C_{LF}, and 650 vs. 531 mg kg^{-1} for C_{min}), demonstrating a strong legacy effect of manure. In addition, the influence of a single manure application on water-stable aggregation remained detectable 22 years later.

Lethbridge Cquest

The Cquest or "Soil Carbon Sequestration" study was established at AAFC Lethbridge Research and Development Centre in 1993 on a Dark Brown Chernozem that had been under wheat-fallow for several decades. The study was designed to evaluate plant C inputs and soil CO$_2$ outputs during the evolutionary or successional stage of agroecosystem development. The experiment included four cropping sys-

Table 8. Harrow Long-Term Rotation site and experimental details.

Site details			
Location	Agriculture and Agri-Food Canada, Harrow Research and Development Centre		
Treaty Territory	McKee Purchase (Ontario Treaty 2, 1790), and the traditional territory of the Ojibwa, Odawa, and Potawatomi		
Mean annual temperature (C)	8.7		
Mean annual precipitation (mm)	876		
Soil type	Orthic Humic Gleysol		
Soil texture	Clay Loam		
pH	6.9		
LTR details			
Name	**Great Lakes Water Quality Study**		Treatments
Soil health management	Amendment	**LCM CDS**	Liquid cattle manure; controlled drainage with sub-irrigation
System	Corn-Soy	**LCM DR**	Liquid cattle manure; regular free drainage
Year established	1991	**SCM CDS**	Solid cattle manure; controlled drainage with sub-irrigation
Design	Four by two factorial randomized complete block	**SCM DR**	Solid cattle manure; regular free drainage
Replication	2	**IF CDS**	Inorganic fertilizer; controlled drainage with sub-irrigation
Plot size	15 m × 70 m	**IF DR**	Inorganic fertilizer; regular free drainage
Notes:	Drain tiles—two 104 mm diameter tiles at 7.5 m spacing and 0.6 m depth	DD CDS	Soil phosphorus draw down; controlled drainage with sub-irrigation
		DD DR	Soil phosphorus draw down; regular free drainage
	1999 treatments changed		
	2006–2007 changed tile depth to 0.85 m and added one tile per plot		
	2006–2007 updated water monitoring technology		
	2008 current treatment regime started		
	Corn—*Zea mays* L.		
	Soybean—*Glycine max* L.		
	Yearly crop grain and stover yields, nutrient uptake and removal, soil P and K, and soil mineral N are recorded		
	Yearly surface runoff and tile drainage flows are recorded with soil P and N losses		
	Surface runoff and tile drainage flows are continuously recorded year-round with soil P and N losses		
	Soil temperature and moisture are recorded for some experimental years		
Name	**Chemical Fertilizer, Various Forms of Pig Manures and Compost Study**		Treatments
Soil health management	Amendment	**CK**	Check
System	Corn-Soy	0P	No P added
Year established	2004	**1IP**	50 kg P ha^{-1} of inorganic phosphorus addition
Design	Randomized complete block	2IP	100 kg P ha^{-1} of inorganic phosphorus addition
Replication	3	2/3IP + 1/3SM	2/3 inorganic and 1/3 solid (straw) pig manure phosphorus addition
Plot size	9 m × 25 m	1/3IP + 2/3SM	1/3 inorganic and 2/3 solid (straw) pig manure phosphorus addition
Notes:	Treatments applied to the corn phase of rotation	**1SM**	50 kg P ha^{-1} of solid (straw) pig manure phosphorus addition

Table 8. (*concluded*).

Site details			
	Corn—*Zea mays* L.	2SM	100 kg P ha^{-1} of solid (straw) pig manure phosphorus addition
	Soybean—*Glycine max* L.	SM-N	Solid (straw) pig manure N-based application
		2/3IP + 1/3LM	2/3 inorganic and 1/3 liquid pig manure phosphorus addition
		1/3IP + 2/3LM	1/3 inorganic and 2/3 liquid pig manure phosphorus addition
		1LM	50 kg P ha^{-1} of liquid pig manure phosphorus addition
		2LM	100 kg P ha^{-1} of liquid pig manure phosphorus addition
		LM-N	Liquid pig manure N-based application
		2/3IP + 1/3MC	2/3 inorganic and 1/3 manure compost (straw) phosphorus addition
		1/3IP + 2/3MC	1/3 inorganic and 2/3 manure compost (straw) phosphorus addition
		1MC	50 kg P ha^{-1} of manure compost (straw) phosphorus addition
		2MC	100 kg P ha^{-1} of manure compost (straw) phosphorus addition
		MC-N	Manure compost (straw) N-based application

Notes: Bold text indicates treatment sampled as part of NAPESHM. Soil data from 0 to 15 cm and collected as part of NAPESHM.

tem treatments: (1) a fallow-spring wheat rotation with both fallow and wheat phases present every year, (2) continuous spring wheat, (3) crested wheatgrass (CWG), and (4) native grasses (NG). Including both annual and perennial crops in these four cropping systems represented systems that varied widely in carbon inputs and outputs in the semi-arid Canadian prairies. The experiment also includes (since 1995) an N fertility factor, where one-half of each cropped plot (i.e., excluding the summer-fallow phases) received ammonium nitrate surface broadcast at a modest 45 kg N ha^{-1} each spring, while the other half remained absent of N fertilization (Table 2).

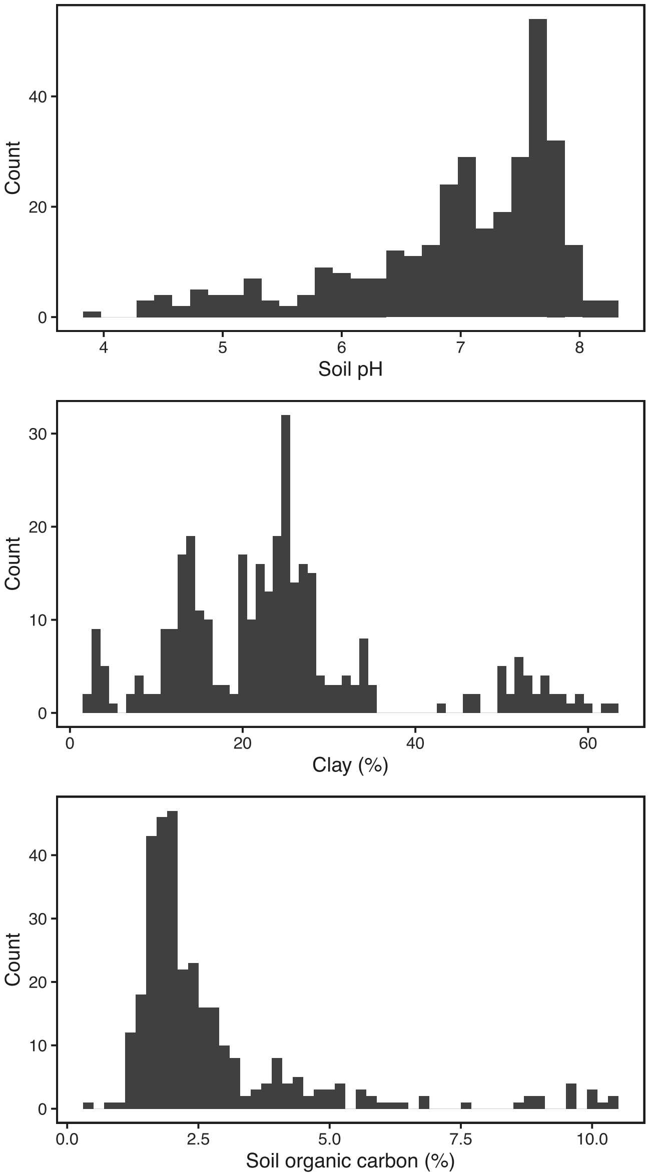
While the soils of the Cquest study continue to evolve, few reports highlighting this study have been published to date. Initial observations suggest that these systems are constrained by N availability, and both above-ground plant production and below-ground SOC accumulation of all systems responded to N fertilization treatments, including the NG (B.H. Ellert, unpublished observation). Aboveground productivity of the NG treatment has been greater and more stable under variable environmental conditions experienced in southern Alberta, likely due to greater utilization of niche space by the community of native grass species.

Soil organic C stock, after the first 12 years, in the 0–30 cm soil layer had increased by 3 and 8 Mg ha^{-1} following perennial establishment of CWG and NG, respectively, compared with continuous wheat (VandenBygaart et al. 2010, 2011). The transition from fallow-wheat to continuous wheat cropping also increased soil organic C stocks in the 0–15 cm soil layer by 3.1 Mg ha^{-1} in this same time frame, but differences were absent at depths >15 cm (VandenBygaart et al. 2010, 2011). In 2017, soil hydrophobicity was 2.1–2.5 times greater in the 0–10 cm soil layer for the perennial CWG and NG plots compared with the annual crop treatments, which corresponded with increases in soil organic C concentration (Miller et al. 2021). The Cquest study is providing insight into the extent to which perennial grasses may restore SOC in annual cropland and provides an excellent resource to study the interdependency of C and N cycling during agroecosystem succession in the semi-arid Canadian prairies.

Onefour Research Ranch

Onefour Research Ranch, initially referred to as the Dominion Range Experiment Station, is located about 40 km northwest of the junction of the Alberta, Saskatchewan, and Montana borders and was not called Onefour until 1965 (Dormaar and Torgunrud 2006; Lawson 2002). It is located in Treaty 7, the traditional territories of the Siksika (Blackfoot), Kainai (Blood), Piikani (Peigan), Stoney-Nakoda, and the Tsuut’ina (Sarcee) First Nations. It was initially established by Agriculture Canada in 1927 to identify problems in southeastern Alberta and southwestern Saskatchewan that included an estimated 4 050 000 hectares of depleted grazing land following the abandonment of numerous homesteads due to poor crop production, inadequate rainfall, high evaporation rates, and grasshoppers (Dormaar and Torgunrud 2006). Initial research priorities included reclamation of over-grazed, weedy farmland, determination of grazing capacity, introduction of grass species for cattle and sheep, water sources for stock, and supplementary winter feeding (Dormaar and Torgunrud 2006). Other official names of Onefour have included, Range Experimental Farm, Manyberries, and the Livestock and Research

Fig. 2. Histograms of soil measurements from the North American Project to Evaluate Soil Health Measurements' Canadian sites. Results for all 333 soil samples representing 101 treatments from 17 sites identifying the range of soil pH, clay content, and soil organic carbon concentration within the Canadian data subset. Soil samples were collected from 0 to 15 cm.



Substation. By 1939 the station had increased in size to 7000 hectares and in 2002 land owned or leased by the Station was greater than 17 000 hectares (Dormaar and Torgunrud 2006).

The ranch is dominated by dry mixedgrass prairie with native grasses or introduced species including CWG and Russian wildrye pastures occurring on previously depleted rangeland. Smoliak and Dormaar (1985) found that while both CWG and Russian wildrye sites produced more forage than the undisturbed dry mixedgrass prairie plots, the native prairie contained more roots and soil organic carbon. A similar study investigating the effects of changing the vegetation on soil properties reported that disturbing the native prairie and reseeding with other grass plantings (CWG or Russian wildrye) decreases soil biological activity for at least the first 2–3 years (Dormaar and Willms 2000). Wang et al. (2010) reported that annual cropping of undisturbed prairie soils resulted in a rapid loss of soil organic carbon in the first 10 years with a transition to a slower rate decrease and a potential new steady state. Other studies have also highlighted effects of wheat farming on native grassland soils (Thomas et al. 2017; An et al. 2019).

Lawson (2002) reviewed Onefour research to date and indicated that soils and grazing research has focused primarily on Brown Chernozemic soils. The paper summarized, amongst many findings, that Onefour's research had established baseline soil properties, shown changes in biochemical processes caused by stresses (such as cultivation, grazing, and the introduction of non-native grass species), and produced valuable information on soil carbon. Studies found that the transition from deep to shallow rooting species caused by heavy grazing changed the properties of the Ah soil horizon, which resulted in it being extremely difficult for the original deep-rooted species to re-establish. The usefulness of CWG for reclamation and rejuvenation was also questioned due to the adverse effects this species may have on potentially increasing bulk density and decreasing stable aggregates (Lawson 2002). Other factors such as soil loss, artificial drought, water-holding capacities, and soil biological activities have also been studied at Onefour (Lawson 2002).

Swift Current 0MC

The "0MC" study (Zero Minimum and Conventional Tillage Study) was initiated in 1981 on an Orthic Brown Chernozem at the AAFC Swift Current Research and Development Centre, in Swift Current, Saskatchewan. The study was designed to investigate the effect of tillage and crop rotation on soil quality and crop production under semi-arid rain-fed conditions of the Canadian prairies. Five cropping systems were established (Table 3), and these included fallow-wheat under conventional tillage (FW CT), minimum tillage (FW MT) and no tillage (FW NT); and continuous wheat under NT (CW NT) and MT (CW MT). Each phase of FW is present every year, and each rotation is cycled on its assigned plots. In 1997, the plots were split into two with one half maintained with the original cropping system and the other with a new system. The new cropping systems from the FW systems were pulse-wheat under NT (PW NT), MT (PW MT), and CT (PW CT), which originated from the FW NT, FW MT, and FW CT, respectively. The same year CW NT was split into CW NT and CW NT (fall glyphosate applied), while the CW MT was split into CW MT and CW MT (reduced N inputs). Further splits were implemented between 2003 and 2008 to briefly investigate organic systems, with some plots being merged again at the end of these brief studies once yields converged. The merging of these splits was completed in 2018. As of 2008, the PW MT became an organic system and was split into GmW CT and GmW reduced tillage (GmW RT). Fertilizer, tillage, weed, and crop management details are reported elsewhere (Tessier et al. 1990; Campbell et al. 1995; McConkey et al. 2003; Maillard et al. 2018).

Findings from this LTR study showed that tillage had no to minor effects on crop yields and residues (Tessier et al. 1990; Campbell et al. 1995; Curtin et al. 2000*b*; Maillard et al. 2018). Tessier et al. (1990) showed that spring wheat yields grown on fallow were more or less similar between NT and CT, except for higher yields on NT in some dry years, while MT fallow resulted in comparable yields to CT in 3 out of 6 years. In addition, tillage reduction increased soil moisture in spring in FW (McConkey et al. 1996), with particularly better soil water conservation in dry summers (Tessier et al. 1990), but this increased soil moisture did not always translate into a yield advantage (McConkey et al. 1996).

0MC identified that changes in SOC and total N were predominantly dependent on cropping frequency (CW vs. FW) rather than on the tillage system (Campbell et al. 1995; McConkey et al. 2003; Maillard et al. 2018) and that NT increased SOC and total N compared to CT, particularly with CW (Campbell et al. 1995; Curtin et al. 2000*b*; McConkey et al. 2003; Maillard et al. 2018). However, changes were mostly observed in the 0–7.5 cm layer. McConkey et al. (2003) reported that NT and continuous cropping increased SOC by 300 kg C ha^{-1} year^{-1}. More recently, Maillard et al. (2018) showed promising results of pulses as a summer fallow replacement to rebuild SOC stocks. The study further highlighted that SOC dynamics in the semi-arid Canadian prairies is highly influenced by precipitation through its impact on both plant biomass C inputs and decomposition.

Other results from 0MC identified that reduction in tillage with adequate crop residue cover increased the production and retention of non-erodible surface aggregates, thereby enhancing protection against wind erosion (Tessier et al. 1990). Adoption of NT coupled with CW increased total P near the soil surface as a result of significant increases in labile to moderately labile P forms, although predominantly in organic forms (Selles et al. 1999). However, NT increased organic N in the top 7.5 cm layer but decreased N availability due to a slower net N mineralization rate (McConkey et al. 2002). This lower N availability implies that higher N fertilizer rates may be necessary under NT systems to take advantage of additional moisture compared to CT (McConkey et al. 1996, 2002). In addition, an economic analysis of the first 12 years of the study found that while NT was best for soil conservation, it generally provided the lowest profitability due to inconsistent and significant yield advantage coupled with a higher production cost, which was mainly linked to herbicide cost (Zentner et al. 1996). Other studies have focused on total and labile organic matter fractions (Liang et al. 2003, 2004), plant diseases (Fernandez et al. 1999), weed communities (Hume et al. 1991), and microbial community composition (Helgason et al. 2009, 2010*a*, 2010*b*).

Swift Current New Rotation

The “New Rotation” was established in 1987 on an Orthic Brown Chernozem at the AAFC Swift Current Research and Development Centre. This LTR experiment was established to incorporate innovations such as conservation tillage, in-soil fertilizer placement (side banding), a new type of spring wheat class (high-yielding CPS wheat), new crop sequences, intermediate length rotations, flexible-type rotations, improved snow management through the use of uniform tall stubble created by direct combining, the use of annual legume green manure, and a perennial grass hay system (Zentner et al. 2003; Lemke et al. 2012b). Nine crop rotations were initially established (Table 3). In 2003, two of the original rotations were discontinued, and the plots were randomly assigned to a new 4-year diversified crop rotation of wheat-canola-wheat-field pea (W-C-W-P). The F-CPS-CPS rotation was changed to fallow-durum wheat-durum wheat (F-D-D) and the CWG was modified to a CWG/meadow brome perennial system in 2016 (Zentner et al. 2006).

A summary of the early findings in this LTR was provided in Lemke et al. (2012b). This LTR has provided strong evidence that an annual legume green manure (lentil in this case) can be successfully used as a partial fallow replacement in the semi-arid Canadian prairies if it is seeded (late April to early May) and terminated early (July) to conserve soil moisture (Zentner et al. 1996, 2004). Results also highlighted the impact of crop rotation and cropping frequency on grain and protein production (Zentner et al. 2003; Smith et al. 2017; St. Luce et al. 2020), water use efficiency (Zentner et al. 2003; Kröbel et al. 2014), and N use efficiency (St. Luce et al. 2020). Recently, St. Luce et al. (2020) showed that rotations with summer fallow were the most stable, well-adapted to poorer growing conditions, possibly low moisture, but less productive overall. The GM-W-W rotation was the least stable and poorly adapted. The ContW system had fairly good stability but was better suited for optimum growing conditions for grain yield. Interestingly, the W-C-W-P rotation consistently produced better than average grain and protein yields and was best suited for optimum growing conditions.

In addition, while SOC increased during the first 12 years in the 0–15 cm layer, crop rotations had no significant effect on SOC gains (Campbell et al. 2000). Interestingly, Campbell et al. (2000) reported that SOC changes are unlikely below 15 cm with shallow tillage under semi-arid conditions. It was noteworthy that while CPS wheat had higher yields and harvest index than Canadian Western Red Spring (CWRS) wheat, it did not increase SOC compared to CWRS, indicating that breeding high-yielding crops with higher harvest index may not necessarily translate to enhanced C sequestration under semi-arid conditions (Campbell et al. 2000). Curtin et al. (2000*a*) noted that the potential for CWG to increase SOC in this semi-arid region will depend on precipitation in early spring which is required for maximum biomass production and C inputs, followed by dry conditions to limit C mineralization. The rich data set from New Rotation has also been used in process-based models to estimate the influence of crop rotations and cropping frequency on grain production and C sequestration (Campbell et al. 2007). In addition, an economic analysis covering the period from 1987 to 2014 concluded that crop rotation profitability increased as fallow frequency decreased (Smith et al. 2017). This study further showed an economic advantage by including oilseed and pulse crops in the rotation.

Indian Head

In 1886, at the edge of the Dark Brown and Black Chernozemic soils, the Indian Head Research Farm was founded. The Farm continues its research today through management by AAFC. Farm research was initially concerned with best-management practices for local conditions, but by the mid-1950s spring wheat sustainability was a concern and in 1957 the Long-Term Rotation study was established (Lafond et al. 2012). Wind erosion through fallow and tillage practices resulted in soil organic matter losses and deterioration of prairie soils and was affecting wheat yields (Hopkins et al. 1946; Awada et al. 2014). The LTR at Indian Head set about addressing these management practices through changes in crop rotations, crop sequences, fertility management, and tillage regimes (Zentner et al. 1987) (Table 4).

After 25 years of management, wheat yields were greater on fertilized stubble treatments and treatments that included green manure or forage in rotation (Zentner et al. 1987). After 30 years of management, studying the influence of fertilizer and straw removal with the LTR study determined that retaining crop residues not only increased soil organic carbon but also increased soil organic nitrogen (Campbell et al. 1991*a*). A crop rotation effect was also reported for 30-year data where soil organic carbon and microbial biomass increased with fertilizer in CW, and the inclusion of green manure or hay in rotation, but not FW and FWW rotations (Campbell et al. 1991*b*). However, with a change in fertilizer protocol in 1978 and the shift to no till in 1990, greater rates of fertilizer were added to the fallow crop resulting in increased yields and soil organic carbon (Campbell et al. 2001*a*, 2001*b*). These results led to the conclusion that carbon inputs from crop residue were the main influence on soil organic carbon (Campbell et al. 2001*a*). Interestingly, Lafond et al. (2009) also showed that the bailing of straw did not remove enough biomass to reduce soil organic matter. With 50-year data, it was clear that the unfertilized treatments had reduced wheat yields due to reductions in soil N and P while the fertilized treatments, in particular those applied to stubble, increased wheat yields (Campbell et al. 2011). In contrast, 50-year data reported no changes in soil carbon for the unfertilized treatments while increased soil carbon was observed with fertilizer application (Lemke et al. 2012a). Long-term data have highlighted the importance of effective fertilization following conversion to no-tillage (Lemke et al. 2010). In summary, results from this study concluded that appropriate application of fertilizers, inclusion of green manure and forage crops, reducing tillage, and converting to no-till farming practices all increased grain productivity and enhanced soil organic matter content (Lafond et al. 2012).

Glenlea Long-Term Rotation

Growth of the organic sector justified a dedicated organic long-term study, which led to the establishment of the Glenlea long-term crop rotation study (referred to as the Glenlea study) by the University of Manitoba in 1992—it is Canada's oldest organic field crop study. The Glenlea study is located 20 km south of Winnipeg on a Rego Black Chernozem and was planned by agronomists, soil scientists, and entomologists who were concerned with the sustainability of fertilizer and pesticide use and wanted to determine if improved crop rotation could reduce the need for inputs, or eliminate them entirely. The study design from 1992 to 2003 provided a 12- year data set where organic, conventional, and intermediate input systems were compared (Entz et al. 2014). Since 2004, the only arable systems include fully organic and fully chemical intensive treatments (Table 5). There are two crop rotations each under organic and conventional management. The grain only rotation includes wheat, flax, oat, and soybean or legume with barley green manure in the organic system. The forage-grain rotations under conventional and organic practices included spring wheat and flax, followed by a 2-year forage mixture. A re-established perennial grassland "benchmark" treatment includes a mix of indigenous warm- and cool-season perennial grasses.

Others have also measured improved soil health in organic compared with conventional systems; for example, Mäder et al. (2002) in the DOK (bioDynamic, Organic and Konventionell) trial in Switzerland. But despite higher levels of soil health indicators at Glenlea, crop productivity in the organic no manure forage–grain system had virtually collapsed after 20 years (Carkner et al. 2020). The yield-limiting factor was phosphorous, which was being removed with hay export. Correcting the P deficiency with manure had an immediate positive effect, more than doubling the organic alfalfa and wheat yields (Entz et al. 2014). Manured alfalfa yields are similar to or slightly greater in organic than conventional production, while wheat yields are on average 24% lower in organic production (Carkner et al. 2020).

Within the first 15 years of organic production, researchers observed a shift in the soil P pools, with less plant available P (Welsh et al. 2009) and more organic P (Braman et al. 2016). In fact, microbial P was more responsive to soil wetting after drought in organic than in conventional production (Braman et al. 2016). The increase in mycorrhizal colonization in organic crops (Entz et al. 2004) and the decline in abundance of non-mycorrhizal weeds (Carkner et al. 2020) were both attributed to less available P in an organic system. Greater mycorrhizal colonization may have been one reason for greater zinc uptake in organic compared with conventional wheat (Turmel et al. 2009). Fraser et al. (2015*a*, 2015*b*) observed greater alkaline phosphatase activity in the low available P conditions at Glenlea and linked greater alkaline phosphatase activity with bacterial phoD gene abundance in soil. Organic systems also resulted in higher levels of dissolved carbon (Xu et al. 2012) and carbon-mineralizing enzymes (SHI 2019 analysis, unpublished). In 2019, the highest levels of soil C were found in the grassland, conventional grain, and organic forage-grain with manure; the lowest soil C was in the grain only organic system (SHI 2019 analysis, unpublished), presumably caused by low levels of biomass production. Organic systems at Glenlea are often found to have a more neutral pH compared with chemically fertilized systems (Welsh et al. 2009); pH was linked to differences in the soil bacterial community between organic and conventional systems (R. Li et al. 2012).

Elora Research Station

In 1980, a rotation trial was started at the University of Guelph's Elora research station on a well-drained Gray Brown Luvisol. Successful introduction of productive corn hybrids into the region during the 1960s resulted in corn becoming the dominant crop during the 1970s. By the late 1970s, there was an increasing realization that corn-dominant rotations, particularly monoculture, were degrading soil structure as well as increasing weed, pest, and disease problems. Hence, there was a need to identify productive and profitable crop rotation options, which led to the establishment of the Elora LTR. The trial consists of eight rotation treatments, continuous corn, continuous perennial forage, and six 4-year cropping sequences (Table 6). The 4-year cropping sequences consist of two consecutive years of corn followed by two consecutive years of alternate crops. These rotations were evaluated under conventional (fall moldboard plow), a conservation tillage system (fall chisel plow (1980–2001), and no-till (2002–present).

Corn yield response to rotation and tillage were already evident by the end of the second 4-year rotation cycle. Specifically, the first year corn yield was less in monoculture compared to following alfalfa or small grain crops (barley or wheat) with the response to rotation larger in the conservation tillage system (Raimbault and Vyn 1991). Also, red clover cover crops established following small grains increased corn yield only in the conventional tillage system. Subsequent reports at the end of rotation cycle 5 (20 years) (Meyer-Aurich et al. 2006*a*) and 9 (36 years) (Janovicek et al. 2021) documented that the corn yield response to rotation and tillage initially reported by Raimbault and Vyn (1991) had increased over time and reaffirmed that red clover cover crops increased corn yield only in the conventional system. Larger yield response to rotation during later years is partially due to greater rates of yield increase over time for first-year corn in rotation with wheat compared to when in rotation with only soybeans or in monoculture (Janovicek et al. 2021). Also, corn yield response to small grains or forage legumes (alfalfa, red clover cover crop) in rotation was especially large during years with unusually hot or dry growing seasons (Gaudin et al. 2015). Larger corn yield response to rotation in conservation tillage systems demonstrated that inclusion of small grains into rotations can minimize the corn yield and profit loss sometimes associated with the adoption of conservation tillage. Soybean response to rotation has also evolved over time. During the initial years, soybean yield was not affected by rotation (Raimbault and Vyn 1991). However, the rate of soybean yield increase over years was larger in wheat-containing rotations compared to when only rotated with corn; resulting in larger soybean yields in wheat-containing rotations during later years (Janovicek et al. 2021).

Soil profile measurements taken 20 years after start of the trial identified that organic C storage in the top 0–34 cm was greatest in the continuous alfalfa and least in the corn-soybean rotation with intermediate storage associated with the corn-corn-alfalfa-alfalfa rotation (Meyer-Aurich et al. 2006b). Subsequent measurements often agreed with these initial findings (e.g., Congreves et al. 2015) with superior C sequestration rates observed in rotations that contain alfalfa or red clover cover crops (Laamrani et al. 2020). Rotations that contain small grains and (or) forage legumes were also observed to have more stable soil aggregates (Congreves et al. 2015; Raimbault and Vyn 1991), greater soil health scores (Chahal et al. 2021; Congreves et al. 2015) and superior soil porosity characteristics (Munkholm et al. 2013). In fact, porosity characteristics between conventional and no-till systems were similar in small grain-containing rotations, which may explain smaller corn yield reductions associated with no-till when rotated with small grains compared to following either only soybeans or planted continuously. In addition, economic analysis identified that during the first 20 years (1982–2001) wheat-containing rotations with straw sales were the most profitable rotation option (Meyer-Aurich et al. 2006a). Larger corn and soybean yield increases when in rotation with wheat during the next 16 years (2002–2017) resulted in the wheat-containing rotations remaining the most profitable rotation option, but now without the need for additional revenue from straw sales (Janovicek et al. 2021). The crop yield response to rotation has yet to achieve a steady state, and future research will continue to monitor rotation effects on crop yields as well as soil properties.

Ridgetown Long-Term Cover Crop

This LTR at the Ontario Crops Research Centre—Ridgetown was established in 2007 and repeated in 2008, an Orthic Humic Gleysol (Chahal and Van Eerd 2018), to evaluate various cover crops in a processing vegetable–grain rotation, that is representative of southwestern Ontario systems. Management depended on the type of the main crop grown; thus, from 2007 to 2021, cover crops were planted 10 times in 14 years (i.e., did not plant cover crops after corn or when winter wheat was grown). Ridgetown main crops are not on a set rotation schedule; however, the first 9 years included peas, sweet corn, spring wheat, tomatoes, grain corn, squash, soybean, winter wheat, and tomatoes. Cover crop treatments for the LTR are oat, rye, radish, and a rye radish mixture with a control treatment (Table 7). Plots were split in some years to either include main crop residue retention or removal. Cover crops are left overwinter, and both crop and cover crop residues are typically incorporated with tillage.

Initial research goals focused on mitigating N losses and weed populations as well as economics (O'Reilly et al. 2012; 2011). Cover crops mitigated N losses in the non-growing season, while in the following season more N was accounted for in crop and soil with cover crops in the system (O'Reilly et al. 2012; Belfry et al. 2017; Chahal and Van Eerd 2021). In the medium term, planting cover crops six times in the first 8 years increased soil health by about 17% but varied depending on the site-year, cover crop treatment, and soil health indicator (Chahal and Van Eerd 2018, 2019, 2021). For instance, surface (15 cm) soil carbon sequestration was 11%–22% greater in plots with cover crops than without (Chahal et al. 2020). In the analysis of both sites over the 8 years, profit margins increased by 5%–9% with radish and rye mix and radish cover crops, which was largely attributed to the revenue gains with processing tomato (Chahal et al. 2020). Compared to a simpler corn–soybean rotation that dominates the Ontario landscape, in this system the inclusion of wheat and vegetables in the rotation allows for a longer cover crop growing season in the fall and hence over 1 Mg ha^{-1} of cereal rye above-ground dry biomass and typically 2–3 Mg ha^{-1} for the other cover crops (O'Reilly et al. 2012; Belfry et al. 2017; Chahal and Van Eerd 2021).

Shifts in microbial communities due to long-term cover cropping influenced early plant growth of tomatoes (Tosi et al. 2022). This has led to current research exploring the potential relationship between soil health and plant health in processing tomato. For example, might cover crop-induced increases in soil health decrease disease incidence (Trueman et al. 2021) or affect fruit quality (Awrey 2021)? Initial results from 2020 and 2021 suggest N deficiency and less corn grain yield without long-term cover cropping (L.L. Van Eerd, unpublished), which leads to the hypothesis that cover crop-induced increases in soil organic matter may be altering C and N cycling and N availability to the corn crop. This is consistent with earlier results where the inclusion of cover crop residues replenished labile organic C pools and reduced C losses in a 72-day incubation study (Ouellette et al. 2016). Future research will include further exploration into the mechanism of soil carbon accumulation.

Great Lakes Water Quality Study

The study was established on a Brookston clay loam soil at the Hon. Eugene F. Whelan Experimental Farm of the Harrow Research and Development Centre, AAFC, Woodslee, Ontario, Canada in 1991 (Table 8). The initial objectives of the study were to test an integrated soil, crop, and water management system to abate herbicide and nitrate contamination of the Great Lakes (Tan et al. 1993). The crop/tillage management treatments included moldboard plow tillage, moldboard plow tillage with annual ryegrass (*Lolium multiflorum* Lam.) intercrop, soil saver, and soil saver with annual ryegrass intercrop. Water management treatments were drainage only and water table control (Tan et al. 1993). Tile drains were intercepted at the border of each plot. Each plot had a surface catch basin to collect the surface runoff. Tile drains and surface catch basins of each plot were connected to the central instrumentation building in which flow volumes were automatically monitored with water samples collected year-round (Soultani et al. 1993). The study proved that water table control combined with soil saver tillage was the best to reduce NO_3-N loss amongst all the treatments tested (Tan et al. 1993).

The second phase of the study introduced in 1999 was to evaluate the effects of organic soil conditioners (i.e., swine manure compost and yard waste compost), winter wheat cover crop, and water table management (i.e., free drainage vs. controlled drainage with sub-irrigation) on crop yield and water N and P nutritional quality (Drury et al. 2014; Zhang et al. 2002, 2013, 2015, 2017). The study identified subsurface tile drainage P loss from fine-textured soils as a critical source for freshwater eutrophication (Zhang et al. 2002, 2013, 2015). Controlled drainage with sub-irrigation effectively reduced various forms of soil P loss (including dissolved reactive P, particular P, and total P) through reductions in flow volume and P concentration in control and yard waste compost treatments, but not with swine manure compost (Zhang et al. 2002, 2015). Cover crop reduced surface runoff while increasing tile drainage volume. Similarly, drainage water management (e.g., controlled drainage with sub-irrigation) increased surface runoff, while reducing tile drainage flow volume. But the total volumes of field water discharge were similar between cover crop and drainage water management. Controlled drainage and sub-irrigation combined with cover crop enhanced reduction in soil particular and total P losses (Zhang et al. 2017).

New treatments of liquid cattle manure and solid cattle manure were imposed in comparison with chemical fertilizer in 2008, while the two drainage water management treatments (i.e., regular free drainage and controlled drainage with sub-irrigation) were retained. A soil P draw-down treatment was also included to evaluate the legacy effects of P previously applied with pig manure compost. All three P addition treatments were designed and implemented in the same approach as for the corresponding treatments (i.e., 50 kg P ha^{-1}, 200 kg N ha^{-1}, and 100 kg K ha^{-1}) in the Chemical Fertilizer, Various Forms of Pig Manures and Compost Study (described next), so that comparisons can be conducted between pig and cattle manures under the same soil-crop-climate conditions. The studies concluded that solid cattle manure was less prone to soil P loss in tile drainage water when the same amount of P was applied (Wang et al. 2018). Utilization of legacy P in soils sustained crop yields, with improved crop production profitability and water quality (T.Q. Zhang et al. 2020).

Chemical fertilizer, various forms of pig manures and compost study

The study was initiated on a Brookston clay loam soil at the Hon. Eugene F. Whelan Experimental Farm of the Harrow Research and Development Centre, AAFC, Woodslee, Ontario, Canada in 2004 (Hao et al. 2015). The initial goals of the study were to develop new knowledge and technologies on nutrient management to improve crop production profitability, resilience to climate change, and soil health benefits of various forms of pig manure in comparison with chemical fertilizers through (*i*) understanding of soil nutrient dynamics and supplying capacity, as well as quantification of the controlling factors; (*ii*) validation of a newly developed soil P environmental testing method for Ontario; (*iii*) evaluation of the long-term legacy of N, P, and K in soils and its agronomic values; and (*iv*) determination of soil health improvement.

Treatments included inorganic fertilizer, liquid swine manure, solid swine manure, and swine manure compost (Table 8). Each of the three organic sources was applied at four rates, including three P-based rates (i.e., 0, 50, and 100 kg P ha^{-1}) and one N-based rate (i.e., 200 kg N ha^{-1}), plus a zero-nutrient (i.e., zero-N, -P, and -K) control. Chemical fertilizer P was added at three rates, including 0, 50, and 100 kg P ha^{-1}. The zero-P rate (i.e., with N and K only) was a shared treatment by all of the four nutrient sources. Other treatments were combinations of inorganic P with each of the three organic sources of P at the ratios of 1/3 and 2/3 to provide a total of 50 kg P ha^{-1}. This formed a total of 19 treatments. All treatments, except for the zero-nutrient control, when needed, were topped up to the same levels of available N (i.e., 200 kg N ha^{-1}) and K (i.e., 100 kg K ha^{-1}) using inorganic fertilizer N and K, respectively, to meet the nutrient requirement for maximum yield production in the region. Fresh solid swine manure was prepared each year consistently with wheat straw as bedding material, and manure compost was prepared each year consistently using liquid swine manure with wheat straw. The application rates for all of three organic amendments were determined based on the nutrients N, P, and K and moisture contents that were analyzed two to three days prior to addition. Corn was grown in the year of initiation, followed by soybean to form a 2-year corn–soybean rotation. Treatments were applied only to the corn phase of rotation.

Data sets on partitioned crop yields, nutrient uptake and removal, soil test P and K, and soil profile mineral N were collected for all treatments every year, along with soil moisture and temperature monitored for the selected treatments. Both crop and soil samples were archived for each of the years during the experimental period. Using the periodical data, responses of crop yields, P uptake and removal, and soil legacy P to selected treatments were summarized (Hao et al. 2015, 2018; Zhang et al. 2021). Phosphorus source availability coefficients (Wang et al. 2016) were determined as 0.99 for liquid swine manure, 1.08 for solid swine manure, and 0.97 for composted swine manure using the approach that takes both long-term crop P uptake and soil test P changes into consideration (Hao et al. 2018). Manure-induced carbon retention coefficients were determined along with other long-term studies across Canada (Liang et al. 2021).

Discussion

Canadian LTRs vary in character, in purpose, and in the original motivating challenge they were set up to solve. The NAPESHM Canadian collection of LTRs covered a multitude of ecoregions (Fig. 1), soil types (Fig. 2), and management systems (Tables 1–8), each is unique and arguably very different from the next. NAPESHM results utilized these existing experiments with a wider network of sites to compare the response of soil measurements to similar soil health treatments across sites (e.g., Liptzin et al. 2022; Rieke et al. 2022; Bagnall et al. 2022). These results highlight the importance of a large and wide network to discern a signal from the noise of highly variable site conditions. Focusing on a Canadian context, further detailed analyses of these data will likely reveal nuances necessary for interpreting these results, and likely identify some unexpected results too. To support future meta-analyses of these data from a Canadian perspective, we describe each Canadian LTR experiment represented in the NAPESHM study (Tables 1–9) to highlight their characteristics and emphasize their value and utility to address persistent, wicked (Batie 2008), and novel questions in soils and agroecosystems. Maintaining them often repays many-fold in the surprising findings they were not originally designed for.

As an example of a surprising finding, Lethbridge's erosion study set out to understand the impacts of erosion, as this was a major concern prior to no-till management becoming standard practice in wind-prone prairie grain agriculture. Topsoils were scraped off to different depths, and yields were examined. The one-time manure application restored yields immediately and continues to show a visible plant vigour and yield benefit after 30 years—and is still detectable in soil health metrics (Larney et al. 2016). A parallel surprising finding in the only organic LTR, the Glenlea study, was that the application of manure increased yields to levels comparable to a conventional system, but also restored subsoil carbon stocks improving soil health (Entz et al. 2014; M.H. Entz, personal comunication). While neither study was explicitly designed to study the impacts of manure on soil health and crop yields, both studies were able to show the importance and efficacy of manure applications to both soil health and crop productivity. Surprising results give us value not predicted in the original design of the experiment.

Further unexpected findings will likely come from studies on soil biology. Advancements in genomics showcase an acceleration of our understanding of microbial controls and levers in building soil health and controlling greenhouse gas emissions and nutrient cycling to support plant productivity. It is now widely accepted that microbiomes play a crucial role in transforming and stabilizing organic matter contributing to ecosystem services such as soil carbon sequestration. While our understanding of how these levers control or are controlled by environmental conditions remains to be determined, theories of microbial contributions abound with evidence building of their importance and clues as to their functionality becoming deciphered (Malik et al. 2020; Domeignoz-Horta et al. 2020; Kallenbach et al. 2016; Spohn et al. 2016; Liang et al. 2017). Understanding the role of microbes will be crucial in building effective global climate models predicting impacts of global climate change, and LTRs provide an excellent platform for deploying genomics approaches to address this.

Another part of the future of LTRs comes from the past and the recognition that many of the LTRs were established at a time in Canadian history when Indigenous traditional territories or knowledge were unlikely to be considered in evaluations of soil management. Since the Truth and Reconciliation Commission offered its report and 94 calls to action in 2015, Canadians and Canadian institutions are more aware of Canada's colonial history and its impact on Indigenous Peoples—and their lands. Land acknowledgements have become popularized, sometimes at the risk of losing meaning (Anderson 2019). We, therefore, highlight the LTRs included in the NAPESHM study span the traditional territories of numerous Indigenous Peoples and Treaty territories to confront soil science's role in Canada's agricultural expansion while Indigenous Peoples were marginalized from their lands and agricultural participation (Arcand et al. 2020; Carter 1993). The establishment of LTRs in Canada parallels the marginalization of Indigenous lands during the establishment of land-grant universities in the United States (Carter et al. 2021), and

Table 9. Historical details and background information for grain crop long-term research (LTR) sites.

LTR sites	Pre-treatment baseline data	Pre-treatment archived soils	Other archived soil samples	Yearly crop yields	Crop nutrient data	Soil sampling frequency	Common soil measurements			Isotopic studies	Gas flux studies	Economic studies	Open data
							Physical	Chemical	Biological				
Breton Classical Plots	–	–	✓	✓	✓	5 years	–	✓	–	✓	✓	–	In-progress
Breton Hendrigan Plots	–	–	✓	✓	✓	5 years	–	✓	–	✓	✓	–	In-progress
Lethbridge Dryland Rotation 120	✓	✓	✓	✓	–	10 years	✓	✓	✓	✓	–	✓	In-progress
Lethbridge Long-Term Manure	✓	✓	✓	✓	✓	5 years	✓	✓	–	–	✓	–	–
Lethbridge Artificial Erosion Dryland and Irrigated	✓	✓	✓	✓	✓	10 years	–	–	✓	–	–	✓	In-progress
Lethbridge Cquest	✓	✓	✓	✓	–	5 years	✓	✓	–	✓	✓	–	In-progress
Swift Current 0MC	✓	✓	✓	✓	✓	Twice a year	✓	✓	–	–	✓	✓	In-progress
Swift Current New Rotation	✓	✓	✓	✓	✓	Twice a year	✓	✓	–	–	–	✓	In-progress
Indian Head	✓	✓	✓	✓	✓	Yearly	✓	✓	✓	–	–	✓	In-progress
Glenlea Long-Term Rotation	✓	✓	✓	✓	✓	2 years	✓	✓	✓	–	✓	✓	In-progress
Elora Research Station	–	–	✓	✓	–	Yearly	✓	✓	–	–	–	✓	✓
Ridgetown Long-Term Cover Crop	–	–	–	✓	–	Yearly	✓	✓	✓	✓	–	✓	In-progress
Great Lakes Water Quality Study	✓	✓	✓	✓	✓	Yearly	✓	✓	✓	–	✓	✓	✓
Chemical Fertilizer, Various Forms of Pig Manures and Compost Study	✓	✓	✓	✓	✓	Yearly	✓	✓	✓	–	–	–	✓

Notes: Check marks indicate data available while dashes indicate data were not collected or applicable. Open data indicate LTR site data are in a digital format and are available for collaboration.

we identify the Indigenous Peoples and their territories as an act of reconciliation by natural scientists (Wong et al. 2020).

Recognition and understanding of the past provide an invitation to soil scientists to look for surprises in the landscapes that had been managed by Indigenous people so that we may learn how these ecosystems might behave in response to our interventions as we have with the LTRs. Imprints of Indigenous people's management interventions on soils across Canada have not been historically acknowledged, likely due to differing world views of the land and human–land (soil) relationships. Instead, any effects of pre-colonial management on the soil reflect those properties present in unmanaged "native" or "natural" ecosystems—ironically sometimes used as a benchmark for soil health (Janzen et al. 2021). Indigenous management effects may never be known to scientists and the body of scientific literature due to an inability to see (because ecological succession or development has erased them), protection of this knowledge and intellectual property by Indigenous People, or ignorance of what to look for and where. However, peer-reviewed literature is starting to report data that demonstrates that some effects of Indigenous management emerge against the "natural" landscape. For example, a recent study in British Columbia revealed higher plant and functional diversity in Indigenous-managed forest gardens located close to archeological settlements compared to outlying forests even 150 years after abandonment (Armstrong et al. 2021). Though this study examined aboveground diversity only, a study of soil biodiversity and soil health is likely to reveal the effects of Indigenous management belowground (Thiele-Bruhn et al. 2012). Indeed, there could be surprises in the soil in landscapes across Canada if we know to look. We have learned from LTRs that daring to be patient and observe over long time scales can uncover important surprises that help us tackle soil problems of the future. Could traditional Indigenous management practices inspire hypotheses to be tested and inform the design of LTRs not yet established?

Soil health and LTR in Canadian agriculture is an ongoing story. Canada's LTRs were an important resource in the past. New LTRs have been initiated in the past few years including AAFC's Living Labs Initiative (Beaudoin et al. 2022; Bronson et al. 2021; McPhee et al. 2021). Through the aforementioned LTRs and NAPESHM project, we are reminded of the value of LTRs for all of us now. In the future, the evolution of the story identifies that LTRs can provide an opportunity to gain unforeseen knowledge and a path to reconciliation. Therefore, it is in our national interest to understand our soil resource and to maintain and expand our LTR network because long-term sustainability is grounded in soil health.

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Data are available from the Soil Health Institute or site Principle Investigators.

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Competing interests

The authors declare there are no competing interests.

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