Making farming more sustainable by helping farmers to decide rather than telling them what to do

R Kröbel¹, E C Stephens¹, M A Gorzelak⁶, M-N Thivierge⁶, F Akhter¹, J Nyiraneza¹, S D Singer¹, C M Geddes¹, A J Glenn¹, N Devillers⁶, A W Alemu¹, M St. Luce¹ and D Giardetti¹

¹ Lethbridge RD Centre, AAFC, AB, Canada
² Swift Current RD Centre, AAFC, SK, Canada
³ Indian Head Research Farm, AAFC, SK Canada
⁴ Brandon RD Centre, AAFC, MB, Canada
⁵ Sherbrooke RD Centre, AAFC, QC, Canada
⁶ Quebec RD Centre, AAFC, QC, Canada
⁷ Charlottetown RD Centre, AAFC, PEI, Canada

E-mail: roland.kroebel@canada.ca

Keywords: Canada, agriculture, sustainability, outreach

Abstract

In Canada, the agricultural sector has long held a prominent economic, social and cultural position, from substantial evidence of extensive fishing and farming since the times of the first human settlements, to currently accounting for over 100 billion dollars of production and employing 2.3 million people. Steady growth in agricultural production in the country over several decades, supported by strong investment in public agricultural science, has allowed an increasing supply of a wide variety of food and agricultural goods to be available both within the country as well as allowing for substantial exports abroad and deep integration of the Canadian agricultural sector into global markets. Along with securing continued productivity growth in agricultural output for the future, policy makers and public sector agricultural scientists in Canada have become increasingly concerned with managing environmental externalities associated with agricultural production in order to achieve the objective of sustainable intensification of the sector. However, the process of identification of the best tools and practices to improve the sustainability of the agricultural sector in Canada has evolved over time due to shifting research priorities and dynamic changes in the problems facing the sector. In this paper we discuss applied and direct-to-farmer agricultural science research initiatives that are focused on identification and implementation of best environmental management practices at the farm level. We believe that involving farmers directly in scientific research and communication of scientific results provides for a deeper understanding of agro-environmental externalities. It also allows farmers to find greater adoption potential in their specific farm system, thus combining both environmental and economic sustainability. We trace the history of public agricultural science engagement with Canadian farmers to address economic and environmental problems in the sector. We then provide examples of successful public sector projects based in applied agricultural science research that foster effective farmer/scientist collaboration, leading to improved agriculture sustainability in Canada.

1. Introduction

Agricultural sciences have had a significant impact on ecosystems in Canada. Wide adoption of key agricultural science innovations, such as high yielding varieties, pesticides, fertilizers and irrigation systems, has resulted in a highly productive agricultural sector for the nation. The ecological consequences of these technologies vary, with some manifesting decades later and only now being researched. Concerns about the impact of climate change, soil health, water quality and availability, global population growth and threats to food security, and recent food price crises have led to increasing attention worldwide on many
dimensions of sustainability for the agricultural sector, including environmental, economic, and social factors like increased inequality across agricultural sectors [1]. Making Canadian agriculture more sustainable and resilient to these and other emergent shocks will increasingly involve understanding and grappling with issues holistically, including tools to assess not only the efficacy of improved production practices but also the environmental impacts of those practices.

Sustainable agriculture falls squarely into the category of ‘wicked problems’—problems that do not have easily identifiable or predefined solutions [2–4], with inherent issues identifying solutions for agriculture that may be universally acceptable, feasible, or even discoverable and agreed upon with any kind of consensus. Scientific solutions are never applied in a political vacuum. Thus, agro-environmental policies often represent not just science-based solutions, but also political bargaining between stakeholders [5]. Agricultural science research thus has a key role in providing information to policy makers and stakeholders on not just improved agricultural yields but also the efficacy of interventions to address environmental issues [5]. A robust agricultural science research program dedicated to both economic and environmental sustainability is critical to identifying a sufficient suite of solutions, tools and interventions to promote sustainable agriculture.

In this paper, we first describe the history of public agricultural science investment and describe the shifting nature of the public sector’s science program objectives to support the agricultural sector. Next, we briefly describe the most important agro-environmental externalities present in Canada that are the focus of agricultural science research past and present. We then describe the main policy tools in place to manage agro-environmental impacts in the Canadian context. And finally, we showcase key public agricultural science research initiatives that have resolved some of the most pressing agro-environmental issues via our consistent scientific engagement directly with farmers. Our objective is to provide multi-faceted examples of governmental agricultural research in Canada to demonstrate that our practice of opening scientific research and solution development to stakeholder input has often been necessary for adoption in real-world situations and will help the agricultural sector find solutions to increasingly complex agro-environmental problems in the future.

1.1. History of public agricultural science investment in Canada

Starting off as an individual scientific enterprise before the end of the 18th century, agricultural science in Canada became a more coordinated search across both public and private research institutions for practical applications to boost agricultural production using modern chemistry [6]. The first Canadian agricultural college was founded in 1873 [7], supported through government policies [6]. Further, the Canadian government set up the Dominion of Experimental Farms System in 1887 for ‘the organized systematic work of experimenting, propagating new varieties, and improving the methods of rational farming’ [7, 8].

Initially setup as five ‘experimental farms’ in 1886, stretching across Canada, a network of 23 accompanying ‘experimental (sub)-stations’ grew over the next decades to better represent and investigate regional agricultural conditions and priority interests [7, 9]. This was complemented by a network of privately owned and farms ‘illustration stations’ (meant to display science-based methods, but often giving rise to new problems and questions), and, after 1915, by parallel provincially led research and education institutions [7]. Much of the focus was on breeding improved varieties, as well as principles of crop and pest management [10], disseminated through publications, meetings, and demonstrations, but also correspondence by letter [7] or by a lecture series provided by train [8]. A designated science service division was founded in 1937, separating basic from applied science [9].

After World War II, moving from simple to complex problems using a team-based approach [6], Canada’s federal agriculture research program expanded its scope and numbers and increased cooperation among all disciplines through establishing a unified research branch [9]. While the early research was aimed to help farmers adapt to local conditions, it turned to improving farm-level production efficiency as well as to supporting industry and market directed research [11]. Outreach directly to farmers continued as a priority, and often using farmer field days to directly demonstrate agricultural science research outputs to the public [9]. In the present day, public, private and non-profit research entities all contribute to the production of agricultural knowledge and innovation in Canada, but the federal government is still a major player in Canadian agricultural research: investing, supporting, and collaborating, while pursuing novel research and the public good [11]. Over time, the objectives of Canadian public investment in agricultural science has changed, from early 20th-century emphasis on scientific advancement to improve agricultural yields, to today’s broader mandate to promote sustainable intensification of agriculture [12]. This results in a public research program that studies impacts of agriculture on the broader environment as well as ways to minimize these impacts while maintaining agricultural productivity. Throughout these changes in priorities, our engagement via
applied research and direct-to-farmer extension have remained important components of our science program. This has enabled substantial innovation in crop and livestock varieties and production practices suitable for diverse Canadian agro-ecological settings and established a robust agricultural sector for the nation. But this investment in agricultural science innovation has also led to the development of several long standing as well as emergent agro-environmental challenges that the next generation of public agricultural scientists must address to improve the sector’s overall sustainability. In the next section, we outline some of the key agro-environmental challenges that the Canadian agricultural sector must address to achieve sustainable intensification, including some agro-environmental problems that were generated by past public sector scientific innovation.

2. Impact of Canadian agriculture and agricultural science on the environment

2.1. Habitat displacement

Agricultural science innovation on crop varieties, farm management and mechanization has enabled a significant level of habitat displacement in Canada. Agricultural production by Canada’s First Nations was limited in size and of little consequence to wildlife habitat [13]. However, with the advent of European colonization, lumber cutting in the coastal areas [14] and subsequent permanent settlement by Europeans [15] left behind a severely altered landscape [16]. Prairie region settlement surged in 1870–1890 (Canada Dominion Lands Act in 1872) [17] after technological innovations enabled dryland farming, and thus continuous cash-crop farming (e.g. wheat) systems [15]. A federal settlement policy in 1900 furthered grassland conversion [18]; of the 61.5 Mha grassland in Canada, 113 000 ha were cultivated in 1881, and 24 Mha in 1931 [19].

Mechanization, freeing up land previously needed to graze draft animals [20], increased cultivation to 50 Mha [19] and the concomitant loss of ~50% of the ephemeral wetlands [21, 22]. The Crown retained rights to free-standing water and wildlife, thus settlers attempted to maximize the land being farmed [22]. Consequently, complex natural habitats were replaced with homogenous crop fields, triggering a decline in biodiversity [23].

Semi-arid mixed grassland ecoregions (SW Saskatchewan and SE Alberta) were settled through corporate ranches [17, 18]. Cattle numbers started with 9000 in 1881 [17, 19], and exploded to ~3.3 million in 1941, coinciding with a time of severe overgrazing [19]. Thanks to adaptive range management, and the appearance of feedlots after 1961, grassland habitats recovered, although cattle numbers continued to climb, reaching the current level of 11 million by 1990 [24].

2.2. Erosion

Soil erosion became an issue when European settlers arrived in Canada [25], and early settlement in Ontario/Quebec caused erosion (and subsequent sedimentation) that irreversibly altered flow and direction of rivers [26, 27]. More recently, agriculture intensified—increased row crop production and a decrease of hay and pasture land [28, 29]—exposing the soil to erosion and degradation [29].

Converting grassland to row crop production can increase erosion up to 300 times, and tilled summer fallow further increases erosion by a factor of 5–6 [30], while the soil organic matter of the A horizon can decrease by 40%–50% [31]. Another important factor in Canadian agriculture is the frozen layer near the soil surface and saturated soil restricting water infiltration, thus increasing the risk of surface runoff [32]. After years of cultivation and widespread summer fallowing (for moisture conservation and weed control) in western Canada, wind erosion and the loss of soil aggregate stability and carbon [33], together with a lack of moisture conserving cropping practices, led to the monumental dust storms of the 1930s [34].

2.2.1. Soil organic carbon loss

Agriculture results in a net loss of soil organic carbon (SOC). It is estimated that 15%–30% of SOC in the top 30 cm layer has been lost in Canada due to cultivation [35] since European settlers arrived. The loss of SOC has well-known consequences, including increased CO₂ emissions to the atmosphere, reduced soil fertility and health, greater risk of soil erosion, loss of productivity, reduced soil microbial activity and diversity [36].

2.3. Excess of nutrients

Nitrogen (N) is the most common limiting nutrient in agricultural production, and the discovery of the Haber–Bosch synthesis [37] allowed replenishing the soil N stocks through synthetic fertilizer [38] in addition to animal manure and N-fixing legumes. As crop and livestock production accelerated by the middle of the century, N surplus in agriculture continued to climb [38]. In 2011, 69% of Canadian farmers applied commercial fertilizers, with the highest application rates in Ontario and Manitoba [39]. Janzen et al estimated that in 1996, approximately 1.12 Tg of N was released to the environment from Canadian agroecosystems [40]. This amounted to an average of 17 kg N ha⁻¹ yr⁻¹ across Canada’s 68 Mha of farmland and a loss of approximately 48% of all N inputs. The role of inorganic phosphorus (P) salts on plant growth was discovered in 1840, and countered degrading soils and dwindling crop yields—mined mineral sources of P became the preferred source [41]. Phosphorus balances have been pushed to surplus through intensive livestock and crop production [42].
Excess N and P from agricultural fields accumulate in freshwater and pose risks to aquatic life and human health (e.g., eutrophication and cyanobacteria algal blooms) [43]. Nitrogen (from synthetic fertilizer or manure) can take directly toxic forms, including un-ionized ammonia, ammonium, nitrate, nitrite, and nitrogen dioxide [43], be transported into lakes and streams, or leached into groundwater [44]. Ammonia is both acutely and chronically toxic to freshwater aquatic species [43, 45], while leached nitrate can pose a human health risk (methemoglobinemia—blue baby syndrome) [46], particularly in shallow groundwater wells (up to 60% of wells in intensive agricultural regions [43]).

By the 1960s, significant declines in water quality were observed in rivers and lakes due to eutrophication [45]. The Ontario Experimental Lakes research identified P as the critical driver [47], leading to regulations on phosphates and wastewater treatment [48]. Regardless, several lakes (and fish production systems) collapsed due to eutrophication [49], e.g., Lake Erie basin, with 12.4 million residents and providing over 50 billion of income [50], is heavily impacted by eutrophication, experiencing episodic harmful algal blooms for over 60 years [51, 52]. Another example is Lake Winnipeg in Manitoba, which observed almost double phosphorus input since the 1990s [53] and is considered to be the eutrophic large lake in the world [54]. The lake which supports over 100 commercial fisheries, generates hydroelectric power, and supplies drinking water, is experiencing a rapid increase in phosphorus loading and concentration through a combination of agricultural inputs and other human activities [53].

2.4. Greenhouse gas emissions

2.4.1. Nitrous oxide
Nitrous oxide (N$_2$O) is a potent greenhouse gas (GHG) with a global warming potential of 265–298 times that of CO$_2$ [55] which contributes to climate change and stratospheric ozone depletion [56]. The atmospheric concentration of N$_2$O is increasing because of agricultural expansion and intensification with current concentrations ca. 20% higher than pre-industrial levels [57]. Most of this increase is attributed to the application of organic and inorganic N fertilizers to cropland soils and the subsequent release of N$_2$O through microbial transformation (i.e. nitrification and denitrification) processes [57, 58].

The Canadian methodology used for national GHG inventory reporting shows that the application of inorganic N fertilizer to cropland soils is the largest anthropogenic source of N$_2$O to the atmosphere, accounting for 23% of agricultural emissions in the country [59]. Inorganic N fertilizer application has grown by more than 70% while N$_2$O emissions attributed to this source have increased by 95% between 1990 and 2016 in Canada [59].

2.4.2. Enteric methane
Ruminant animals have a unique advantage of being able to utilize and convert fibre/feed into food (high-quality protein and energy) as well as graze on arable lands not suitable for crop production (two-third of the world’s agricultural land). As such, humans rely on a few livestock species such as cattle, buffalo, sheep and goats as a food source. However, the digestion of fibre/feed in the rumen by microbes produces enteric methane (CH$_4$) as a by-product. Methane is not only an energy loss (2%–12% of total energy consumed) to the animals but also a potent GHG, with a global warming potential of ~86 times stronger per unit mass than CO$_2$ on a 20 year time scale and 28 times more powerful on a 100 year time scale [60]. A recent analysis indicated that global CH$_4$ emissions rose by nearly 10% over the past two decades (since 2000), mainly driven by agriculture and the natural-gas industry [61, 62]. Methane from enteric fermentation contributed about 6% and 46% of the total global anthropogenic GHG and CH$_4$ emissions, respectively [63]. Similarly, 41%–52% of Canadian agricultural GHG emissions are contributed by enteric methane emission [39]. The much shorter life-time of CH$_4$ (half-life; 8.6 years [64]) in the atmosphere, compared to CO$_2$, make it an attractive target for short-term gains in global warming abatement.

2.5. Livestock breeding and welfare
After domestication, farm animals evolved along with humans following both a relaxation of selection from their natural wild environment and an unconscious and conscious selection by humans [65]. Over time, specific morphologic, behavioural or functional characteristics were selected. As a result, farm animals became generally bigger, leaner, more prolific, less fearful and grew faster [66]. Intensification on productivity aspects led to co-selection of undesirable traits such as reproductive problems, metabolic disorders, leg weakness, and higher susceptibility to stress [66–68].

In parallel to genetic selection, management and housing of animals drastically evolved over the past century towards more confined and barren conditions with more indoor, high density, automated husbandry systems and increased use of antibiotics. For example, the average number of animals on farms increased from 14 to 1677 for pigs and from 151 to 6086 for chicken and hens between 1951 and 2016 in Canada [69]. Intensification of animal production while allowing expression of the full potential of highly selected productivity traits by better controlling feeding, environmental conditions and monitoring of animals also drove them to their biological limits and ended up diminishing their welfare [70]. Indeed, domestic animals’ behavioural needs are most similar to wild species and are generally not
fulfilled by the artificial conditions in which they live [71, 72].

2.6. Crop breeding and genetic manipulation
Crop breeding efforts have shifted over the millennia of documented human plant domestication, from individual farmer experimentation for desired traits through selection [73–75] to the development of hybrids [76], and then of Mendel’s principles on trait inheritance to boost an expansion in breeding technology [77]. In the 1930s, induced mutagenesis using radiation or chemicals began to be applied to crop breeding [78, 79]. These discoveries resulted in the Green Revolution (1960s), which transformed wheat, maize and rice production through an increase in the use of irrigation, pesticides, fertilizer, as well as the development of high-yielding varieties [80]. Professional breeders have continued breeding since (with a variety of additional molecular and biotechnological tools added to the breeding toolbox). While breeders have technically replaced the farmer as the breeder, their aim is still to serve their interest, but perhaps in a more efficient manner [81, 82]. Despite many successes over the years, crop breeding can also result in reduced crop genetic diversity [83, 84] and decreased crop diversity through an increase in monoculture production systems [85–87]. This results in increased vulnerability to disease and/or pest infestation [88], thus posing a limit to conventional breeding endeavours [89]. The move to transgenic varieties has also triggered both health and environmental concerns [90], though no such effects could be proven [91]. Rather, reduced herbicide and pesticide use overall (reviewed by [92]), with little to no change in soil fauna [93] or microbial [94–96] abundance/composition were observed.

2.7. Biotic pests and pesticides
Weeds, insects, and pathogens pose a significant threat to global production of food, fuel, and fibre. Weeds represent the largest potential crop loss (about 34%), while potential losses from animal pests and pathogens are estimated to be somewhat lower (about 18% and 16%, respectively) [97]. Farmers have always struggled with pest control, and in Canada, public research has provided farmers with timely information on the utility of pest management practices since the early work of the Dominion Experimental Farms System in the late 1800s [8].

While weed management prior to World War II consisted predominantly of mechanical control practices (e.g. tillage), modern weed control in the form of synthetic herbicides co-developed with chemical warfare [98, 99]. Following World War II, and the success of the phenoxy herbicide 2,4-D, among others, interest in herbicide discovery grew and new herbicide modes of action were discovered and released steadily up until the mid-1980s [100].

While pesticide use can benefit crop production by helping farmers mitigate and manage biotic threats to the agroecosystem, application of synthetic or xenobiotic chemicals to farmlands raises concerns over pesticide persistence in soils, and pesticide residues in food products, and unintended impacts on environmental and human health [101]. Public scrutiny of pesticides can raise awareness resulting in more-extensive pesticide safety testing, but may also threaten crop productivity due to risks of deregulation of effective pest control products (e.g. current scrutiny of neonicotinoid insecticides [102] or the herbicide glyphosate [103]), regardless of the grounding of some concerns in sound scientific evidence.

2.8. Emerging agro-environmental issues and agricultural science research
In addition to the externalities identified above, there are many more unintentional and emerging threats to agricultural sustainability that will require agricultural science research attention to understand and identify solutions. A topical example is the issue of microplastic contamination in terrestrial systems [104]. Microplastic contamination of agricultural soils is a by-product of many current agricultural practices (e.g. use and improper disposal of mulching films [105]), as well as an important source of aquatic microplastic contamination [106]. Current research on the impact of microplastics on agricultural soils in the Canadian context is limited. Existing legislation on microplastics in Canada (the Canadian Environmental Protection Act was updated in 2018 to include microplastics) has not yet been expanded to consider the agricultural context. Further research is needed on the sources, fate, and ecological and human health risks associated with microplastics entering the soil food web in agricultural areas to inform future policy and decision-making regarding mitigation.

3. Economics, the environment and agricultural science policy
Agriculture in Canada traditionally has focused on economic stability and support for the sector. Government policy intervention in agriculture is justified by the fact that it is a sector with a relatively high degree of risk in comparison to other sectors, due to dependence on highly variable environmental conditions and market prices [107]. Current farmer support estimates for Canada are valued at approximately 5.7 billion CDN [108], the vast majority of which goes to different agricultural sector economic stabilization programs [107, 109]. However, support for the sector also includes significant investment in public agricultural science at the nation’s 21 Research and Development Centres spread across the country, Agriculture and Agri-Food Canada—Science and Technology Branch (AAFC-STB).
Beyond economic considerations, there is increasing attention being paid to the environmental impacts of Canadian agriculture and more attempts made to use agricultural policy to address those concerns as well as for economic stabilization. There is also more direct scrutiny of the environmental consequences of our economic stabilization and support policies, given that they have encouraged production and thus broadened the environmental impact of agriculture [107].

Agro-environmental policies to address externalities associated with agricultural production can generally take the form of command-and-control style regulations of practices and standards to be followed or incentive-based mechanisms that encourage agricultural producers to internalize the costs of environmental impacts of agriculture in order to adopt better management practices to reduce these costs [110]. Both policy approaches have costs and benefits. Payments to farmers and financial incentive programs can be more effective than regulations as they encourage farmers with the greatest capacity to mitigate environmental impacts to take the largest steps [110]. Policy-makers in general cannot identify these farmers independently, thus these tools also resolve some information problems associated with managing externalities through regulation.

However, on the negative side, designing the incentive programs themselves to match up appropriately with the true environmental costs can be difficult, due to measurement issues, particularly for non-point source pollution, which is one of the main environmental impacts of agriculture. There are significant data gaps and uncertainties and a lack of market price information about agricultural externalities that make estimation of these costs difficult [111]. Agricultural science research can bridge some of these data gaps, particularly on better understanding of the biophysical processes and consequences of agricultural activities on the environment, as well as identifying solutions to improve management of these processes to limit negative externalities.

In Canada, negative agro-environmental externalities are managed both with regulation at the federal and provincial levels (like the Great Lakes Water Quality Agreement, or zoning legislation with respect to siting restrictions for farming activities), as well as through incentive and payment schemes such as the ALUS land conservation program, which provides annual payments to farmers that invest in ecosystem services on their land, like maintaining riparian buffer zones. These programs also recognize that maintaining the environmental resilience in the natural resources managed by the agricultural sector builds up the country’s overall sink capacities to absorb negative environmental shocks. However, most of the negative externalities from the agricultural sector are managed through government regulations as well as through voluntary, industry-led standards [112]. For farmers, complying with policies and regulations can impose additional costs, like investing in improved on-farm waste management systems for example, or switching to different pest control products and procedures. It also can be difficult to demonstrate the impact of improved management practices on environmental outcomes of interest to take advantage of incentive payment programs. Today, practicing agriculture is a pressure cooker. Farmers face commodity price fluctuations, vilification in public perceptions of their practices, debt due to high investment costs, increases in prices for fuel, land, and machinery, all while managing natural systems responding to an ever-increasing unstable climate [113]. Minimizing environmental externalities may come last in this juggling act. Nevertheless, farmers are highly educated and engaged with agricultural science which has a long history of direct-to-farmer information exchange that can also help move the sector forward to increased economic and environmental sustainability through farm-level research efforts. Farmers also provide critical insights to agricultural science researchers on where to look for optimal scientific solutions to agro-environmental externalities.

Cost-sharing and direct farmer payment programs, to encourage adoption of a selected set of best management practices are thus common in implementation of agro-environmental policies, like Alberta’s agricultural carbon offset program (www.alberta.ca/agricultural-carbon-offsets-overview.aspx). For both cost-sharing and regulatory policy approaches, a key issue is identification of best management practices and regulatory standards that achieve the maximum environmental impact. Enforcing compliance with poorly designed standards or providing cost-sharing programs to encourage incorrectly identified best management practices ultimately will reduce attempts to manage environmental impacts from agriculture. Cross-compliance approaches to agro-environmental policy that combine environmental standards with receipt of agricultural income support payments bridge some of the complex trade-offs involved in achieving environmental sustainability in agriculture [109]. Participatory research at the farm level has also shown promise in identifying better and more feasible practices by also confronting complex relationships in farming communities and finding new ways to resolve complex questions about resource allocation [114]. This type of farm-level research is practiced across many of the public agricultural research branches at the federal and provincial level in Canada.

4. Outreach (or how much can Ag scientists influence what is going on?)

Agricultural science has produced many success stories (agriculture in the Canadian prairies would not be what it is without science), and yet, many of the
problems we are facing today were arguably caused by these success stories in the first place. Almost all of the early successes in agricultural science focussed on higher productivity and better food security, but that progress had consequences that were seen only much later (higher yield potential required fertilization, causing GHG emissions and eutrophication as a consequence). Government policy paradigms have therefore changed to no longer focus exclusively on higher productivity, but to also understand the interaction with the environment and to investigate how farming could become more sustainable. Initial science results around productivity and efficiency were often welcomed and readily adopted due to the contributing important economic benefits to farmers, but where environmental recommendations are promoted today, other (economic or agronomic) considerations often dominate discussion. It is there that scientists realize that they have fewer means to enforce behaviour, and instead must find different pathways to approach the communities in order to help them decide and showcase consequences of agricultural management choices and practices [115]. There is a long history in Canada of public investment in agricultural science to resolve key problems for the sector. The scope initially focused on research designed to improve agricultural productivity and has now expanded to incorporate ecological issues that both impact and are generated by the agriculture sector. The history and development of a public agricultural research program in Canada, with its focus on finding solutions to problems of direct interest to farmers, will provide a good platform for conducting research that can enhance both economic and environmental sustainability in the future through established systems of communication between farmers and scientists and investment in methods to disseminate agricultural innovation and research findings. We highlight below many different examples of Canadian public agricultural science innovation and stakeholder engagement that have been developed to solve some of the key agro-environmental challenges in the sector past and present.

5. Solutions

5.1. Habitat creation/preservation
Agroforestry practices such as shelterbelts helped to bring some lost habitat back to agricultural land by the beginning of 1900, promoted through AAFC’s Prairie Shelterbelt Program (1903) to address soil erosion [116]. The program supplied agricultural producers with over 600 million free trees and promoted shelterbelts by providing design guidelines and maintenance information. While the program’s primary aim was to combat soil erosion through trees as windbreaks, planting shelterbelts also offered a complementary role in providing habitat at a landscape level. These shelterbelts provide food, browsing area, breeding and nesting ground, shelter from inclement weather, a refuge from predators, and safe travel corridors between habitat areas [117]. Across Canada, shelterbelts and other agroforestry systems, such as riparian plantings and alley cropping, were documented to increase the diversity and abundance of plants [118], mammals [119], avian communities [120–123], native bees [124] and other beneficial insects [121], benthic insect and fish diversity [125], and soil microbial communities [126–128].

5.2. Nutrient retention
To minimize nutrient contamination risk, the 4R Nutrient Stewardship (Right Source, Right Rate, Right Time, Right Place) aims to focus nutrient management on matching fertilizer supply to crop requirements [129]. Other strategies, such as intercropping and crop rotation, serve to increase fertilizer recovery [130, 131]. For in-field livestock feeding systems, the use of impermeable base pens and containment ponds can reduce nutrient leaching and runoff [132]. Riparian buffer strips are a means of stabilizing streambanks while trapping nutrient-laden sediment and contaminants just before they reach the watercourse [133], though it is viewed as deprivation of productive cropland [134].

Between 2004 and 2014, AAFC’s Watershed Evaluation of Beneficial Management Practices program enhanced land-use decision making at the farm and landscape levels [135]. The program developed and tested beneficial management practices (BMPs) that demonstrate a reduction in nutrient loading to surface water at a small watershed scale by implementing those on farms and assessing their effect. For example, the construction of small on-farm earthen dams reduces sediment, N, and P loading to streams by reducing downstream peak flow and rainfall-runoff. Other BMPs, such as controlled tile drainage, cattle exclusion fencing, streambank fencing, and conservation tillage, also prevent nutrient runoff in the receiving water body.

Regulations targeting nutrient management exist at both the federal and provincial levels. The Canadian Environmental Protection Act regulates nutrients that contribute to the growth of aquatic vegetation. In 1993, Ontario developed the Environmental Farm Plan (EFP) program, which helps farmers develop site-specific environmental action plans to identify and implement BMPs [39]. The program now operates in all provinces, through mainly voluntary participation. In 2017, 40% of Canadian farms had an EFP [136].

5.3. Carbon sequestration and erosion prevention
The development and adoption of no-tillage cropping systems in Canada started in the mid-1980s to
goals and results with farmers at events such as field days and producer group-led conferences, the introduction of farmer checkoffs as a means of raising funds to supplement research over the past few decades has allowed the re-calibration of program targets in certain cases. This promotes a sense of connection between farmers and breeders, and enables the interests of growers to be reflected in breeding program aims.

However, there appears to be a lack of willingness of some farmers to fund government-led research compared to university breeding programs [154], which suggests that a gap remains in these interactions. Furthermore, while this system may work well for breeding endeavours that will directly benefit farmer profit margins, there is also a need to ensure funding for the improvement of traits with no immediate financial benefit, such as those that could enhance environmental sustainability or are of value for public good. For example, research is currently underway to develop new crop cultivars with improvements in traits related to photosynthesis/carbon sequestration, grain quality and N fixation capacity, as well as those with the potential to reduce GHG emissions from the agricultural sector.

5.5. GHG mitigation

As GHGs in agriculture stem from multiple interactive sources, mitigation efforts are hampered through trade-offs and ripple effects. To ease the burden of cost and labour, whole-farm modelling has gained prominence to investigate mitigation options on farms. In Canada, the whole-farm model Holos was developed by agricultural scientists, and is designed to be utilized by farmers to explore the effect of their management decisions on their whole-farm GHG budget [155].

5.5.1. Nitrous oxide

Solutions for reducing soil N$_2$O emissions from Canadian cropland could include the use of enhanced-efficiency N sources and site-specific application of conventional fertilizers. Enhanced-efficiency N fertilizers, including products containing nitrification and/or urease inhibitors, and slow-release (e.g. polymer-coated) forms have been shown in many studies to reduce soil N$_2$O emissions to the atmosphere without negatively impacting crop yield or quality, especially under environmental conditions where losses are favourable [156, 157]. A global meta-analysis of 35 studies suggested that nitrification inhibitors, in particular, appear to be the most consistent technology at reducing fertilizer-induced losses of N$_2$O from agroecosystems [158].

Barriers to adoption of enhanced-efficiency N fertilizers by farmers include the need to further verify agronomic performance and economic return on products that cost significantly more than conventional sources of inorganic N such as urea [159]. Site-specific or variable rate application of
N fertilizer is another potential solution for reducing soil N₂O emissions from Canadian agriculture. Recent research in southern Manitoba has found significantly lower fertilizer-induced N₂O emission factors for high-yield compared to low-yield production zones [160]. This study conducted by AAFC scientists with a local farmer-led research association highlights a possible win–win opportunity for farmers whereby tailoring N applications to crop requirements within fields could potentially reduce both GHG emissions and input costs.

5.5.2. Enteric methane
Designing practical strategies for enteric CH₄ mitigation requires fundamental knowledge of the rumen biochemistry and microbiology. Over the past few decades, animal research has been shifted to understanding the factors affecting rumen fermentation process (methanogenesis) as well as exploration of different mitigation strategies in an effort to reduce enteric CH₄ emissions. These strategies are designed to: (a) improve animal productivity and efficiency, (b) improve nutrition, (c) decrease rumen methanogenesis, and (d) improve animal breeding [161, 162]. Technological progress further permits assessing feeding behaviour and quantifying feed consumption of animals [163], understanding rumen fermentation [164], and quantifying the amount of enteric CH₄ production [165].

Although several mitigation strategies have been proposed, many are difficult to apply on-farm due to either having low mitigation potential or being at an early stage of development. Among the developed strategies, the use of chemically synthesized inhibitors including 3-nitrooxypropanol (3-NOP) and the addition of sea weed (macroalgae) are the most promising [161]. Studies report that feeding 3-NOP to beef and dairy cattle can reduce enteric CH₄ yield (g CH₄ kg⁻¹ dry matter consumed) by 20%–40% [166]. This product is currently under evaluation on-farm to support licencing by government authorities and will play a significant role in minimizing emissions from ruminant agriculture once approved. Furthermore, recent studies with marine macroalgae showed tremendous potential for CH₄ mitigation, with an average reduction of 42% in beef and dairy cattle [167]. However, the continued expansion of ruminant animal industry, the cost of mitigation options, the difficulty of applying mitigation strategies to grazing animals and the inconsistent effect of mitigation on animal performance are the major constraints for decreasing global enteric CH₄ emissions from ruminants [161].

5.6. Livestock welfare and sustainability
In Canada, apart from animal cruelty laws and transport and slaughter regulations, there are no regulations of farm animals’ conditions of life. However, since the 80s, Codes of practice for farm animals have been developed with the participation of all the stakeholders in each animal production system, including scientists, in order to set minimum standards for the management and housing of animals [168]. Thanks to a constructive discussion between industry representatives, animal protection organizations and the scientific community, some of these codes have been translated into real changes on farms, such as group-housing in gestating sows, through the implementation of quality assurance programs led by the industry and thus widely adopted by farmers.

Beyond animal welfare, new paradigms in agriculture and especially in animal production have emerged in the last decade to rethink production systems according to more holistic and ecological principles. For example, the One Health concept promotes an integrative and systemic approach of the human, animal and environmental health [169]. Another example is agroecology applied to animal production which offers new principles to design sustainable animal production systems based on improving animal health, decreasing the inputs of production, decreasing pollution, enhancing diversity and strengthening their resilience, and finally preserving biological diversity in agroecosystems [170].

The implementation of such integrated approaches of animal production systems can also include participatory methods in order to better engage farmers [171]. Such systems also require new orientations of breeding programs focussing on robustness and individual adaptive capacities [172–174]. However, these systemic approaches are not yet widely adopted.

5.7. Biobeds
Moving forward, sustainable farming will require a balance of chemical and non-chemical pest control, grounded in careful and judicious pesticide use. In addition to continued research on how farmers can manage pests sustainably while reducing pesticide use (i.e. integrated pest management), other innovations like pesticide biobeds show promise in helping farming operations manage pesticide waste by promoting retention and degradation of pesticide molecules before they can be leached into the environment [175–177]. Adoption of new innovations, like pesticide biobeds, require close cooperation of farmers, researchers, and outreach personnel, and it is movements like this that are driven at the farm level.

5.8. Additional outreach activities and the living labs initiative
Field days continue to be a favourite for farmers. Principles and consequences are clearly visible, and scientists are present to deal with additional questions and viewpoints (or as a source for further information and understanding) [115]. Newspapers (such as La Terre de Chez Nous in Quebec since 1929, or the Western Producer in the Canadian prairies since 1923) are an independent broker of information for
farmers, trusted by farmers for their better understandability and the farming context they provide. AAFC also uses Facebook, LinkedIn, and Twitter platforms to share innovations that directly impact farmers and hosts a web page that features federal researchers (https://profils-profiles.science.gc.ca/en), their areas of expertise and key accomplishments, providing more direct access for the general public.

Sustainability indicators, such as the Indicateurs de Durabilité des Entreprises Agricoles Québec (IDEA)-QC method developed by AAFC that combines 40 sustainability indicators for a participatory assessment with the farmer, or models such as Holos, are means with which scientific understanding can be transferred to farmers to explore decision making consequences. Moreover, a new form of participatory research is emerging in the form of the Living Laboratories initiative.

The Living Laboratory initiative is based on three core principles: (a) user centred innovation; (b) real life experimental setups; (c) and private-public-people partnerships [178]. The collaboration between scientists and stakeholders and an integration of knowledge including natural sciences and social sciences allows solving agro-environmental solutions while also addressing barriers to the adoption of beneficial agricultural management practices by growers. Following a presentation by Canada during the G-20 meeting of Agricultural Chief Scientists in Argentina in 2018, the International Agroecosystems Living Laboratories group was formed. The working group (with representatives from Argentina, Canada, European Commission, France, Germany, Japan, Mexico, New Zealand, Turkey, United Kingdom and United States) has the mandate to develop a framework to strengthen collaboration and to promote dialogue, standardization and knowledge sharing [179]. The Canadian Living Laboratory network was launched in 2019 and innovative research trials in real life conditions are underway across the country [178].

Farmer participatory research offers multiple advantages including: (a) providing opportunities for researchers to gain different perspectives including information that has been passed down from generations of farmers or indigenous knowledge [180, 181]; (b) generating local relevant solutions and adaptation capacity to enhance environmental performance [182]; and (c) finding efficient solutions to problems by testing out alternative on-farm techniques and empowering farmers to innovate and adapt [183, 184]. The above-mentioned advantages result in strengthening the trust between farmers and scientists.

Current trials that are part of the Living Laboratory Initiative target many agricultural practices meant to offer solutions to the negative externalities of agricultural production while enhancing ecosystems services. These practices, like agroforestry, perennial groundcover, regenerative grazing management, no-till and cover crops, are associated with regenerative agriculture. Numerous definitions of regenerative agriculture exist and are either based on agricultural processes/practices (e.g. crop rotations, integration of crop–livestock operations), outcomes/objectives (e.g. increased soil carbon, increased biodiversity) or both [185, 186]. Nevertheless, restoring soil health appears as one of the cornerstones of regenerative agriculture [186] and aims to not only preserve, but to improve the state of resources [187]. Farmers themselves have been at the forefront of regenerative agriculture [187], and since 2015 science is catching up, as shown by the drastic increase in publications [185]. Few empirical studies, however, have explored how to foster and maintain the transition by farmers towards regenerative agriculture, which appears driven by experiential learning [188]. The Living Laboratories initiative provides the space where farmers can share their trial-and-error approach to accelerate and enrich this transition experience. Participatory research based on co-design and co-development of potential solutions, as with the living laboratories initiative, seems an efficient way for farmers and scientists to engage in a learning process [188] based on regenerative agriculture.

6. Conclusion

Canadian investment in agricultural science has been critical to the growth and development of the sector but has also been responsible for introducing many of today’s agro-environmental challenges that impact long term environmental and economic sustainability. With a long history of stakeholder engagement and inclusion of farmers in the scientific research process, public sector agricultural science as currently practiced in Canada is well-positioned to identify the most appropriate interventions to improve environmental sustainability by incorporating farmer knowledge, feedback and context into the search for solutions. Even so, many challenges remain in encouraging greater adoption of scientifically identified best management practices, even with an established set of public science institutions and documented history of success. As demonstrated with the given examples, successful implementation of solutions is taking place where farmers have been included in the research process. These partners are indispensable: as knowledge recipients and translators (making it accessible to other peers), as co-designers and demonstrators of the implementable solution, and as a result, also communicators. For scientists in non-agricultural sectors seeking to change society, we believe following the lessons from public agricultural science and identifying, accepting, learning from and collaborating with non-academic partners like farmers can be key for developing solutions in other sectors that can be more readily adopted by the general public.
Data availability statement

No new data were created or analysed in this study.

Acknowledgments

Significant contributions to pesticide research and Biobed development and implementation in Canada were performed by Dr Claudia Sheedy, whose research, innovation, and friendship are deeply missed in our community. We dedicate this manuscript to her memory.

Funding was provided by Agriculture and Agri-Food Canada as part of the Canadian Agricultural Partnership (CAP) program.

ORCID iDs

M A Gorzelak https://orcid.org/0000-0002-4115-5282
M-N Thivierge https://orcid.org/0000-0003-0246-2746
N Devillers https://orcid.org/0000-0002-5866-9394

References

[1] Qualman D 2019 Tackling the farm crisis and the climate crisis: a transformative strategy for Canadian farms and food systems National Farmers Union-Discussion document (Saskatoon: NFU 2019)
[2] DeFries R and Nagendra H 2017 Ecosystem management as a wicked problem Science 356 265–70
[3] Batie S S 2008 Wicked problems and applied economics Am. J. Agric. Econ. 90 1176–91
[4] Rittel H and Webber M 1973 Dilemmas in general theory of planning 155–69
[5] Fulton M 2015 Agricultural policy in the 21st century: economics and politics Can. J. Agric. Econ. 63 7–18
[6] Russel S E J 1966 A History of Agricultural Science in Great Britain, 1620–1954 (London: Alien and Unwin)
[7] Snesarev V N 1930 Dominion experimental farms system (Agriculture Canada, 1886–1986)
[8] Groh H 1922 A history of weed control and investigation in Canada Sci. Agric. 3 415–20
[9] Anstey T H 1986 One Hundred Harvests: Research Branch, Agriculture Canada, 1886–1986 (Ottawa: The Branch)
[10] DoE 1939 Fifty years of progress on dominion experimental farms 1886–1939 Printer to the King's Most Excellent Majesty ed D E Farms (Ottawa: J.O. Patenaude, I.S.O.)
[11] AIC 2008 Agricultural Institute of Canada. An overview of the Canadian agricultural innovation system (#320-176 Gloucester Street, Ottawa)
[12] AAFC What we do (available at: www.agr.gc.ca/eng/about-our-department/what-we-do?id=136700688523)
[13] Patterson T R, Dalby A, Kumar A, Henderson I A and Boudreau R E A 2002 Arcellacens (thecamoebians) as indicators of land-use change: settlement history of the Swan Lake area, Ontario as a case study J. Paleolimnol. 28 297–316
[14] Loo J and Ives N 2003 The Acadian forest: historical condition and human impacts For. Chron. 79 462–74
[15] Russel P A 2012 How Agriculture Made Canada: Farming in the Nineteenth Century (Montreal & Kingston: McGill-Queen's University Press)
[16] MacDowell L S 2012 An Environmental History of Canada (Vancouver: UBC Press)
[17] Williams W, Adams B and Mckenzie A 2011 Overview: anthropogenic changes of Canadian grasslands Arthropods of Canadian Grasslands vol 2, ed K D Floate (Lethbridge: Biological Survey of Canada) pp 1–22
[18] Jefferson R G, Iwaasa A, Schellenberg M and McLeod J G 2013 Re-evaluation of native plant species for seeding and grazing by livestock on the semiarid prairie of western Canada Prairie Forum 38 275–304 (https://www.nps.gov.ca/docs/2.pdf/Re-evaluation_of_Native_Plant_Species_for_Seeding_and_Grazing.pdf)
[19] Wang X, VandenBogaart A J and McConkey B C 2014 Land management history of Canadian grasslands and the impact on soil carbon storage Rangeland Ecol. Manage. 67 333–43
[20] Olmstead A L and Rhode P W 2001 Reshaping the landscape: the impact and diffusion of the tractor in American agriculture, 1910–1960 J. Econ. Hist. 61 663–98
[21] Bartzen B A, Dufour K W, Clark R G and Caswell F D 2010 Trends in agricultural impact and recover of wetlands in prairie Canada Ecol. Appl. 20 525–38
[22] HSD 1994 Sustainability of Canada's Agri-Food System—A Prairie Perspective (Winnipeg: Faculty of Agricultural and Food Sciences: University of Manitoba)
[23] Benton T G, Vickery J A and Wilson J D 2003 Farmland biodiversity: is habitat heterogeneity the key? Trends Ecol. Evol. 18 182–8
[24] Canada S 2021 Table 32-10-0130-01 Number of cattle, by class and farm type (x1000) (https://doi.org/10.25318/32100130-0301-eng)
[25] Lau G 2011 Ongoing Soil Degradation in Canada and Its Impacts on the Future of Soil Productivity (Vancouver: University of British Columbia)
[26] Eyles N, Meriano M and Chow-Fraser P 2012 Impacts of European settlement (1840–present) in a Great Lake watershed and lagoon: Frenchman's Bay, Lake Ontario, Canada Environ. Earth Sci. 68 2211–28
[27] Karst T L and Smol J P 1998 Tracking the cultural eutrophication history of Collins Lake (southeastern Ontario, Canada) using paleoecological techniques Lake Reservoir Manage. 14 456–65
[28] Sparrow H O 1984 Soil at risk: Canada's eroding future (Senate of Canada, Ottawa)
[29] Miller M H 1986 Soil degradation in eastern Canada: its extent and impact Can. J. Econ. Can. 33 7–18
[30] Lohr M L and van Kooten G C 1995 Is soil erosion a problem on the Canadian Prairies? Prairie Forum 20 167–21
[31] McGill W B, Campbell C A, Dormaar J E, Paul E A and Anderson D W 1981 Soil organic matter losses. Agricultural land: our disappearing heritage—a symposium Proc. 18th Annual Alberta Soil Science Workshop (Edmonton, Alberta)
[32] van Vliet L J and Wall G J 1987 Soil erosion losses for winter runoff in southern Ontario Can. J. Soil Sci. 61 451–8
[33] Rennie D A 1985 Soil degradation: a western perspective Can. J. Agric. Econ. 33 19–29
[34] Samson F B, Knopf F L and Ostlie W R 1998 Grasslands Status and Trend of the Nation's Biological Resources vol 2, ed M J Mac, P A Opfer, C E Puckett Heacker and P D Doran (Reston, VA: U.S. Department of the Interior, U.S. Geological Survey) pp 437–72
[35] Janzen H, Campbell C, Gregorich E and Ellert B 2018 Soil carbon dynamics in Canadian agroecosystems Soil Processes and the Carbon Cycle (Boca Raton, FL: Taylor and Francis) pp 57–80
[36] Lal R 2003 Soil erosion and the global carbon budget Environ. Int. 29 437–50
[37] Smil V 2001 Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food (Cambridge, MA: MIT Press)
adopt beneficial greenhouse gas nitrogen management practices through fertilizer management Can. J. Soil Sci. 97 801–4
[160] Glenn A J, Moulin A P, Roy A K and Wilson H F 2021 Soil nitrous oxide emissions from no-till canola production under variable rate nitrogen fertilizer management Geoderma 385 114857
[161] Beauchemin K A, Ungerfeld E M, Eckard R J and Wang M 2020 Review: fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation Animal 14 s2–s16
[162] Hristov A N et al 2013 Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO2 emissions eds Pierre J. Gerber, Henderson Benjamin and Harinder P.S. Makk 177 (Rome: FAO animal production and health) pp 1–228
[163] Gonzalez I A, Kyriazakis I and Tedeschi L O 2018 Review: precision nutrition of ruminants: approaches, challenges and potential gains Animal 12 s246–s61
[164] Dijkstra J, van Gastelen S, Dieho K, Nichols K and Bannink A 2020 Review: rumen sensors: data and interpretation for key rumen metabolic processes Animal 14 s176–s486
[165] Hristov A N et al 2018 Symposium review: uncertainties in enteric methane inventories, measurement techniques, and prediction models J. Dairy Sci. 101 6635–74
[166] Dijkstra J, Bannink A, France J, Ke rebra e B and van Gastelen S 2018 Short communication: antimethanogenic effects of 3-nitrooxypropanol depend on supplementation dose, dietary fiber content, and cattle type J. Dairy Sci. 101 9041–7
[167] Kinley R D, Martinez-Fernandez G, Matthews M K, de Nys R, Magnusson M and Tomkins N W 2020 Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed J. Clean. Prod. 259 120836
[168] Bradley A and MacRae R 2010 Legitimacy & Canadian farm animal welfare standards development: the case of the National Farm Animal Care Council J. Agric. Environ. Ethics 24 19–47
[169] Tarazona A M, Ceballos M C and Broom D M 2019 Human relationships with domestic and other animals: one health, one welfare, one biology Animals 10 1–21
[170] Dumont B, Fortun-Lamothe L, Jouven M, Thomas M and Tichit M 2013 Prospects from agroecology and industrial ecology for animal production in the 21st century Animal 7 1028–43
[171] Ryschawy J, Moraine M, Pêquignot M and Martin G 2018 Trade-offs among individual and collective performances related to crop–livestock integration among farms: a case study in southwestern France Org. Agric. 9 399–416
[172] Knap P W 2005 Breeding robust pigs Aust. J. Exp. Agric. 45 1–11
[173] Phocas F et al 2016 Review: towards the agroecological management of ruminants, pigs and poultry through the development of sustainable breeding programmes II Breeding Strategies Animal 10 1760–9
[174] Phocas F et al 2016 Review: towards the agroecological management of ruminants, pigs and poultry through the development of sustainable breeding programmes I–selection goals and criteria Animal 10 1749–59
[175] Bergevinson J, Perry B J, Sheedy C, Braul L, Reedyk S, Gossen B D and Yost C K 2018 Identifying the core bacterial and fungal communities within four agricultural biocasts used for the treatment of pesticide rinsates J. Appl. Microbiol. 125 1333–42
[176] Castillo M, Torstensson L and Stenstrom J 2008 Biocasts for environmental protection from pesticide use—a review J. Agric. Food Chem. 56 6206–19
[177] Vischetti C, Capri E, Trevisan M, Casucci C and Perucci P 2004 Biomassed: a biological system to reduce pesticide point contamination at farm level Chemosphere 55 823–8
[178] AAFC Living Labs 2020 Living laboratories initiative: government of Canada (available at: www.agr.gc.ca/eng/scientific-collaboration-and-research-in-agriculture/living-laboratories-initiative/?id=551383721157)
[179] MACS-G20 2019 Agroecosystem living laboratories
[180] Mapfumo P, Mtambanengwe F and Chikowo R 2015 Building on indigenous knowledge to strengthen the capacity of smallholder farming communities to adapt to climate change and variability in southern Africa Clm. Dev. 8 72–82
[181] Lobry de Bruijn L, Jenkins A and Samson-Liebig S 2017 Lessons learnt: sharing soil knowledge to improve land management and sustainable soil use Soil Sci. Soc. Am. J. 81 427–38
[182] Grabowski P, Musumba M, Palm C and Snapp S 2018 Sustainable agricultural intensification and measuring the immeasurable: do we have a choice? Routledge Handbook of Sustainability Indicators and Indices ed S Bell and S Morse (Abingdon: Taylor and Francis)
[183] Wortmann C S, Christiansen A P, Glewen K L, Hejny T A, Mulliken J, Peterson J M, Varner D L, Wortmann S and Zou bek G L 2007 Farmer research: conventional experiences and guidelines for alternative agriculture and multi-functional agro-ecosystems Renewable Agric. Food Syst. 20 243–51
[184] Bezner Kerr R, Snapp S, Chirwa M, Shumba L and Msachi R 2007 Participatory research on legume diversification with Malawian smallholder farmers for improved human nutrition and soil fertility Exp. Agric. 43 437–53
[185] Newton P, Civita N, Frankel-Goldwater L, Bartel K and Johns C 2020 What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes Front. Sustainable Food Syst. 4 577723
[186] Schrefel L, Schulte R P O, de Boer J J M, Schri jver A P and van Zanten H H E 2020 Regenerative agriculture—the soil is the base Glob. Food Secur. 26 100404
[187] Burns E A 2020 Placing regenerative farming on environmental educators’ horizons Aust. J. Environ. Educ. 1–11
[188] Gosnell H, Gill N and Voyer M 2019 Transformational adaptation on the farm: processes of change and persistence in transitions to ‘climate-smart’ regenerative agriculture Glob. Environ. Change 59 101965