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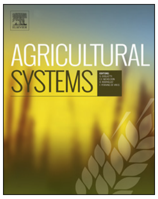

A meta-analysis approach to examining the greenhouse gas implications of including dry peas (*Pisum sativum* L.) and lentils (*Lens culinaris M.*) in crop rotations in western Canada

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ABSTRACT

This study used a meta-analytic approach to systematically examine changes in greenhouse gas (GHG) emissions intensities (i.e., carbon footprints) between pulse-containing and pulse-free crop rotations in western Canada. A systematic literature review was conducted to identify published literature relevant to the goal of the analysis and meta-analysis was conducted to determine statistically significant differences in GHG emissions between pulse-free and pulse-containing crop rotations. Four pulse-free reference rotations (cereal-cereal [C—C]; oilseed-cereal [O—C]; oilseed-oilseed [O—O]; and cereal-oilseed [C—O]) were compared to rotations where the first crop in each two-year sequence was replaced with either dry pea (*Pisum sativum* L.) or lentil (*Lens culinaris* M.). Two scenarios were considered. The first scenario investigated the effects of dry peas and lentils when synthetic nitrogen (N) applied to cereal and oilseed crops grown after pulses was not reduced (i.e., no change) (N_N). The second scenario (N_{CR}) investigated the effect of dry peas and lentils when synthetic N application rates were reduced to the maximum extent possible (i.e., credit) to maintain subsequent crop yields. Pooled analyses demonstrated that, in general, cereal and oilseed crops grown after a dry pea or lentil crop had similar or reduced GHG emissions compared to those grown after a cereal or oilseed. The GHG emissions from cereal and oilseed crops grown after dry peas and lentils were higher in N_N (888–987 kg CO_2e/ha; 286–598 kg CO_2e/t) than in N_{CR} (311–978 kg CO_2e/ha; 116–598 kg CO_2e/t), suggesting that emissions were reduced to a greater extent when pulse crops offset the N fertilizer requirements of a subsequent crop compared to when they were used to provide N to maximize crop yields. In two-year rotations, the inclusion of pulses reduced GHG emissions compared to all reference rotations in both N_N (savings of 475–719 kg CO_2e/ha over two years [area basis]; 164–496 kg CO_2e/t over two years [yield basis]) and N_{CR} (savings of 489–1185 kg CO_2e/ha over two years [area basis]; 335–610 kg CO_2e/t over two years [yield basis]), mostly as a result of reduced synthetic N requirements of the whole rotation. The results of the analysis are presented by crop for each pulse-free and pulse-containing cropping sequence for each scenario to allow for flexibility in comparing GHG emissions from various rotations.

1. Introduction

Food systems, including preproduction, production, and post-production activities, are estimated to contribute approximately 19–29% of total global anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012). The agriculture sector is the largest contributor to global anthropogenic nitrous oxide (N_2O) and methane (CH_4) GHG emissions (Smith et al., 2014). In the effort to reduce GHG emissions from food systems while striving to meet current and future global food demands, opportunities to reduce GHG emissions from food systems must be considered throughout the food supply chain. This includes crop production practices. This is particularly important considering climate change is projected to result in increased variability in temperature and precipitation, extreme weather events, water scarcity, and incidence of pest and disease outbreaks (FAO, 2016b), each of which has the potential to affect the ability of cropping systems to meet the requirements of future global food demands.

One of the largest contributors to GHG emissions from the agriculture sector is the production and use of synthetic nitrogen (N) fertilizers. Over the last half century (i.e., 1961–2010), global emissions from synthetic fertilizer have grown at an average rate of almost 4% per year (Smith et al., 2014). Considering current trends, the International

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Panel on Climate Change (IPCC) predicts that synthetic fertilizers will overtake manure deposited on pasture to become the second largest contributor of all agricultural emission categories within the next ten years, following only enteric fermentation (Smith et al., 2014). It is important to recognize however, that the increased use of synthetic fertilizers has helped drive an increase in global grain production.

The most effective way to reduce GHG emissions from cropping systems is to reduce GHG-intensive inputs to the system while maintaining or increasing productivity (MacWilliam et al., 2014). Given its relatively large contribution to the carbon footprint (i.e., total GHG emissions per unit basis) of crop production, it is logical to examine the potential for reducing and/or optimizing the amount of synthetic N applied to cropping systems as a method for reducing the GHG intensity of grain production. However, N is an essential nutrient for crop growth and reducing its application rate may lead to nutrient deficiencies and a decrease in crop yields. This suggests that, rather than simply reducing the application rate of N fertilizer, alternative methods for supplying N to crops may be more effective in decreasing GHG emissions. In western Canada, pulse crops such as dry pea (*Pisum sativum* L.) and lentil (*Lens culinaris* M.) have been shown to reduce the synthetic N requirements of crop rotations and increase the yield and quality of grain grown after the pulses; particularly in cereals (Badaruddin and Meyer, 1994; Lin and Chen, 2014; Miller et al., 2003b). Dry pea and lentil do not typically require synthetic N due to their unique ability to fix N from the atmosphere. Furthermore, these pulse crops have been shown to contribute to meeting the N requirements of subsequent crops, thus reducing the synthetic N requirements of the full two-year cropping sequence (Zentner et al., 2001).

In 2016, pulse crop production in western Canada accounted for approximately 98% of the total Canadian pulse production; however, only 10% in Alberta, 18% in Saskatchewan, and 1% in Manitoba of total principle field crop area was dedicated to dry pea and lentil (Statistics Canada, 2017). Despite the relatively low area dedicated to pulse production, Canada was the world's largest producer of dry pea and lentil, contributing 35% and 48% of the total supply, respectively (STAT Communications Ltd., 2017). Given the scale of total crop production in western Canada, the potential for increasing pulse production, and the prospective N-related benefits of dry pea and lentil to crop rotations, opportunities may exist for developing crop production strategies that better utilize pulses as a method for decreasing GHG emissions from cropping systems. A number of studies have examined the effects of pulses in cereal and oilseed crop rotations on the N fertilizer requirements and the N cycle of crop rotations in western Canada (e.g., Khakbazan et al., 2016; Dusenbury et al., 2008; Badaruddin and Meyer, 1994). However, differences in location, growing conditions, management practices, and results across studies present challenges for ascertaining definite conclusions about the effects of including pulse crops in cropping systems. In the case that the combined results of these studies clearly indicate a reduction in required synthetic N fertilizer and an associated reduction in GHG emissions from the use of pulse crops in cropping systems, an opportunity exists to increase and/or modify the use of pulse crops to improve the environmental performance of crop production, and food systems.

The goal of this work was to use a meta-analytic approach to determine the statistically significant effects of either dry pea or lentil in annual cropping systems in western Canada on the GHG emissions intensities of crop production systems. Meta-analysis was selected as the approach for the analysis as its primary purpose is “to combine the results of a number of different reports into one report to create a single, more precise estimate of an effect” (Ferrer, 1998). The benefits of meta-analysis include: 1) The provision of better estimates of relationships in a population compared to single studies; 2) An increase in the amount of data and statistical power, leading to improved precision in estimates; 3) Allowance for the examination of hypothesis testing and biases; and 4) Helps to resolve inconsistencies in research (Stone and Rosopa, 2017).

The objectives of this study were to: 1) Systematically review the literature and compile agronomic and emissions data corresponding to yield, protein levels, N fertilizer application, soil organic carbon (SOC), energy input, and GHG emissions from studies that compared western Canadian cereal and oilseed cropping systems with and without peas and lentils; 2) Use meta-analysis to statistically determine the effects of dry peas and lentils on agronomic and emissions outcomes of subsequently grown cereals and oilseeds in western Canada; and 3) Apply data derived from objectives 1 and 2 to develop improved carbon footprints of pulse-free and pulse-containing cropping systems. The results of this study are intended to support and inform the development of strategies for improving the environmental performance of cropping systems in western Canada. For this study, the term “pulses” refers to dry peas and lentils.

2. Materials and methods

2.1. Overview

A systematic literature review was conducted to identify published literature reporting agronomic or emissions data with comparisons between pulse-free and pulse-containing crop rotations in western Canada. All data points of potential significance to the GHG emissions of cropping systems reported in the literature were extracted for further analysis and a series of plots were generated to examine the relationships between data points. Relationships were identified and maintained through statistical analysis. Statistically significant differences between pulse-free and pulse-containing crop rotations were identified using meta-analysis for each set of data points where the data were sufficient in number and either consistent in format or able to be standardized into comparable formats. The results of the meta-analysis were supported by literature from the systematic review to estimate the effects on GHG emission intensities (i.e., carbon footprints) from the production of pulse-containing and pulse-free crop rotations. Additional information on the methodology for each stage of the project are provided in Sub-Sections 2.2-2.5.

2.2. Systematic literature review

A systematic review of English-language, peer-reviewed literature using EBSCO*host* (EBSCO Information Services, 2016a), EBSCO Discovery Service (EBSCO Information Services, 2016b), AGRIS (FAO, 2016a), and PubAg (USDA, 2016) databases was conducted to identify literature relevant to the goal of this analysis. Literature selected for inclusion in the meta-analysis met the following criteria: 1) Studies were conducted in the field (i.e., studies conducted exclusively in a lab or greenhouse were excluded); 2) Studies reported data on principal field crops grown in crop rotation and for grain (i.e., intercropping, green manure, and forage crops were excluded); 3) Studies were reporting on dry pea, lentil, or both; 4) Direct comparisons between pulse-containing and pulse-free rotations were made; 5) New data were reported (i.e., review studies were excluded unless they reported previously unpublished data); and 6) Studies were conducted in western Canada (Manitoba, Saskatchewan, Alberta).

For comparison to pulse-containing rotations, the following four pulse-free rotations were identified based on the data from the systematic review and used as reference sequences: cereal-cereal (C—C), oilseed-cereal (O—C), cereal-oilseed (C—O), and oilseed-oilseed (O—O). Each of these reference sequences was compared to a sequence where the first crop in the sequence was replaced by either dry pea or lentil. Data relevant to the goal and scope of the analysis were extracted on a trial-by-trial basis from each paper during the systematic review. The extracted data included: crop yield; grain protein content; N fertilization rates; cropping sequence; study specifications including location (s), number of trials, and years of study; GHG emissions; fossil energy requirements; any information pertaining to the N cycle of the cropping system (e.g., soil nitrate levels); residue yields and nutrient contents; and soil organic carbon (SOC). Given this method, studies reporting more field trial replicates, years, and/or locations contributed more data points to the meta-analysis.

In order to maintain the inherent relationship between data points from the same study (i.e., same location, soil type, climate, and crop management activities), direct comparisons were only made between crops within the same study at the same location and during the same year. An extensive exploratory analysis using graphical plots and Analysis of Variance (ANOVA) was conducted to determine where relationships existed between data points. The results of the exploratory analysis indicated that N fertilizer application rates were correlated to crop yield and cereal protein content. To best capture the relationship between N fertilizer application, and yield and quality effects, two scenarios were considered. In the first scenario (N_N), the nitrogen application rates were the same (i.e., no change) for cereal and oilseed crops in both the pulse-containing and pulse-free reference rotations and these rotations were analyzed to examine the changes to yield of cereal and oilseed grains grown after a lentil or dry pea crop. Changes to the protein contents of cereal grains were also examined as an indicator of grain quality. Literature did not provide evidence that including pulse crops in an oilseed-based rotation affected the quality of oilseeds, and as such, oilseed quality was not assessed.

In the second scenario (N_{CR}), the data were examined to determine the extent to which the amount of synthetic N fertilizer applied to cereals or oilseeds grown after a pulse crop could be reduced (i.e., nitrogen credit) to maintain the yields observed in well-fertilized cereals or oilseeds in the reference rotations. In this scenario, a stepwise approach was used to filter the data. In the first step, the percent changes in crop yields for crops grown after a pulse compared to the reference crops were plotted against the associated change in applied N fertilizer. From these plots, the approximate range for each rotation in which the reduction in N fertilizer resulted in no changes to crop yields between the pulse-containing and pulse-free rotations were identified. In the second step, data extracted from the systematic review that fit within the identified data ranges were selected for inclusion in the N_{CR} scenario and were evaluated in the same manner as in the N_N scenario. In the P—C vs C—C comparisons, yield increases occurred even when N fertilizer was not applied. In these cases, the data were filtered to include only studies reporting results for pulse-containing rotations where N fertilizer was not applied.

At the onset of this study, the systematic review included the Northern Great Plains (NGP) of Canada and the United States (US) with the intention of conducting the analysis for the broader region. However, as a result of the limited data available for the US that met the inclusion criteria of the systematic review, it was determined that an analysis of the entire NGP was not possible. As such, the data from the US were excluded from the study and the results presented in this paper are specific to western Canada. However, to provide additional information to the literature, where possible, an expanded systematic review and analysis that included both the US and Canadian data was conducted. This expanded analysis is referred to as the NGP analysis and the corresponding results and discussion are presented in Supplementary Materials. The addition of data from the US permitted the addition of a summerfallow-cereal (F—C) reference rotation; a practice that is primarily representative of cropping systems in the US.

2.3. Meta-analysis of differences in yield, protein content, and N fertilizer

A meta-analytic approach was employed to analyze available data for effects on outcomes related to crop production. The software package 'R' (The R Foundation, 2016) was used to isolate the data required for each scenario (N_N and N_{CR}) and to perform statistical analysis on the yield, N fertilizer rate, and effects on protein content of including either dry pea or lentil in rotation compared to the pulse-free reference rotations of cereal and oilseed crops. For each scenario, the mean yield increase in cereals and oilseeds in pulse-containing rotations compared to pulse-free rotations was recorded along with the standard error of the mean yield increase. For cereal crops, the mean protein increase was also recorded along with its standard error.

2.4. Estimating the carbon footprints of pulse-containing and pulse-free cropping systems using the results of the meta-analysis

2.4.1. Determining yield and fertilizer application rates in pulse-free and pulse-containing rotations

For the reference rotations, averaged multi-year (1993–2011) crop yields for barley and wheat (all) were calculated to estimate cereal yield (grain ha^{-1}) (Statistics Canada, 2017). Data from the same period were used to estimate the average annual oilseed, dry pea, and lentil yields (Statistics Canada, 2017). Similarly, real-world N and phosphorous fertilizer rates reported by producers in western Canada in the Canadian Field Print Initiative Survey for 2014 and 2015 (Canadian Field Print Initiative, 2014/2015) were used as a baseline for pulse crops (i.e., lentil and dry pea), as well as cereal and oilseed crops in the pulse-free reference rotations.

Results from the meta-analysis for differences in yield (N_N and N_{CR}) and levels of N fertilizer applied to achieve similar yields of cereal and oilseeds (N_{CR}) were used to derive the yield and fertilizer application rates in pulse-containing cropping systems compared to the pulse-free reference rotations.

Across reference rotations and pulse-containing scenarios, the methodology for estimating total GHG emissions (i.e., carbon footprints [kg CO_2e ha^{-1}]) for pulse-free reference and pulse-containing cereal and oilseed rotations (N_N and N_{CR}) is summarized below. Total GHG emissions were determined from: 1) The production and acquisition of cropping inputs (i.e. fertilizers, pesticides, and seed); 2) Field operations (i.e., fuel use for planting, tilling, applying pesticides and fertilizers, and harvesting); and 3) Direct and indirect nitrous oxide (N_2O) emissions from managed soils.

Crop production activity data were converted to GHG emissions estimates using IPCC global warming potential (GWP) factors (Myhre et al., 2013) and the carbon footprints were developed by summing emissions estimates from each activity required for crop production. The data and methods for estimating emissions from each stage of crop production are described in the following sub-sections.

2.4.2. Emissions from cropping inputs: Fertilizer, pesticides, and seed

To account for potential differences in GHG emissions from the production of different types of fertilizers, the proportions of each type of N fertilizer (e.g., urea) applied per hectare to each type of crop (i.e., cereals or oilseeds), as reported in the Canadian Field Print Initiative Survey (Canadian Field Print Initiative, 2014/2015), were used to determine the GHG emissions from the production and acquisition of N fertilizers per hectare for cereals and oilseeds. The survey reported average N fertilizer application rates of 86 kg N/ha for cereals, and 112 kg N/ha for oilseeds. The survey data showed the type of N fertilizer most applied to both cereals and oilseeds was urea (58% of the total nitrogen volume applied to cereals, 53% for oilseeds), followed by anhydrous ammonia (31% for cereals, 38% for oilseeds), urea ammonium nitrate (7% for cereals, 5% for oilseeds), and the remaining 4% being comprised of a variety of other fertilizer types used in comparatively small amounts. The emission factor for the production of each type of N fertilizer were from the DataSmart life cycle inventory (LCI) data package (Long Trail Sustainability, 2016), which is the North American version of the European-centric ecoinvent LCI (ecoinvent, 2017). The weighted emission factors for the production and acquisition of N fertilizer based on the proportions of each type of fertilizer applied were 3.48 kg CO_2e/kg N for cereals and 3.31 kg CO_2e/kg N for oilseeds (ecoinvent, 2017).

Phosphorous fertilizer application rates were also taken from the Canadian Field Print Initiative surveys for 2014 and 2015 (Canadian

Field Print Initiative, 2014/2015). Meta-analysis data were not applied to phosphorous rates in reference rotations as application rates were not found to differ from growing pulse crops before cereals and oilseeds. Average phosphorous application rates were 30 kg P_2O_5/ha for cereals, 33 kg P_2O_5/ha for oilseeds, and 13 kg P_2O_5/ha for pulses. Monoammonium phosphate was the dominant source of phosphorous applied to both cereals (91% of total volume of phosphorous-based fertilizer applied to cereals) and oilseeds (85% of total volume applied to oilseeds). Ammonium phosphate was the second-most applied source of phosphorous, contributing 6% of total volume applied to cereals and 11% for oilseeds. The remaining 3% and 4% of total applied phosphorous to cereals and oilseeds, respectively, was from diammonium phosphate. The emission factor for the production and acquisition of monoammonium phosphate (1.62 kg CO_2/kg P_2O_5; Long Trail Sustainability, 2016) was assumed for all applied phosphorous.

The GHG emissions from the production of seed for planting the crops were derived from MacWilliam et al., 2014 using seeding rates from the 2016 Crop Planning Guide for Saskatchewan (Government of Saskatchewan, 2016).

Emissions from the production and acquisition of pesticides (39 kg CO_2e/ha for pulse-free rotations, 35 kg CO_2e/ha for pulse-containing rotations) were averages taken from all literature sources from the systematic review reporting emissions data for pesticides (Bremer et al., 2011; Gan et al., 2011a; Gan et al., 2011b; Sainju et al., 2014; Zentner et al., 2004; Zentner et al., 2001).

2.4.3. *Emissions from field operations*

Emissions from the use of fuel for on-farm activities such as seeding, tilling, applying plant protection productions, and harvesting were averages from the GHG and energy input data from the systematic review (included data from Bremer et al., 2011; Gan et al., 2011a; Gan et al., 2011b; Sainju et al., 2014; Zentner et al., 2004; Zentner et al., 2001). Energy inputs for field operations that were reported in units of energy (e.g., GJ) were converted to GHG emissions using the energy content factor for diesel (0.0387 GJ/L) reported by the National Energy Board (2016), and the United States Environmental Protection Agency (2014) emission factors for the combustion of diesel fuel in non-road agriculture equipment (CO_2 = 2.7 kg/L, CH_4 = 0.00038 kg/L, N_2O = 0.000069 kg/L). The average GHG emissions from on-farm fuel use was 119 kg CO_2e/ha for pulse-free rotations and 114 kg CO_2e/ha for pulse-containing rotations. Greenhouse gas emissions from the production, distribution, storage, and disposal of on-farm capital goods (i.e., on-farm equipment) have been shown to be minor contributors to the total carbon footprint of grain production (Frischknecht et al., 2007; MacWilliam et al., 2014); however, these emissions estimates are largely dependent on the assumed lifespan of the equipment as well as the use of the equipment during its lifespan. Given the high uncertainty and potentially large variance in the estimated lifespans of on-farm equipment, and the expectation that emissions from farm equipment will not differ significantly as a result of including pulse crops in otherwise pulse-free cropping systems, emissions from capital good were excluded from this analysis. In the case that more precise estimates of equipment lifespans become available, and the contribution of equipment to the carbon footprint of grain production is found to be significant, the results of this study should be amended to include emissions from capital goods.

2.4.4. *Nitrous oxide (N_2O) emissions from managed soil*

Nitrous oxide is naturally present in soil as a by-product of nitrification and denitrification (De Klein et al., 2006). The amount of N_2O produced in soils is related to the availability of inorganic nitrogen in the soil. Data on various aspects of the N cycle of pulse-free and pulse-containing crop rotations were extracted as part of the systematic literature review; namely differences in straw yield and N uptake, total N accumulation in straw and grain, N mineralization, nitrate-N levels of the soil, N content of residues, and measured N_2O emissions and fluxes. However, these data were not directly comparable or suitable for meta-analysis due to differences in study methodologies, goals, and/or data format, comprehensiveness, or granularity. In addition, data points represented select stages of the N cycle and were not able to be compiled to represent the full N cycle of a pulse-free crop rotation in comparison to a pulse-containing rotation. To remain consistent in the approach across all cropping systems, the data from the systematic review were not used in estimating N_2O emissions from managed soils. Alternatively, N_2O emissions from managed soils were estimated using the IPCC Tier II (direct) and Tier I (indirect) methodology (De Klein et al., 2006). In the Tier II approach, the default ratios and N contents of above- and below-ground residues were replaced with Canadian-specific factors from Janzen et al., 2003. In addition, an averaged emission factor (0.0048 kg N_2O-N ha^{-1} yr^{-1}) specific to the western-Canadian context from Rochette et al., 2008 for direct N_2O emissions was substituted for the IPCC default factor. Ammonia emissions from urea application were included in the N_2O emissions calculations from indirect sources and the default IPCC factor (0.010 kg N_2O-N kg N^{-1}) was used. Likewise, the IPCC default factors for fraction of N lost through leaching in dryland soil (0.10 kg N kg N^{-1} applied) and for N_2O emissions from leaching (0.0075 kg N_2O-N kg N^{-1}) were used.

2.4.5. *Global warming potential*

The most recent IPCC GWP factors including climate-carbon feedback (CO_2 = 1 kg CO_2e/kg CO_2; CH_4 = 34 kg CO_2e/kg CH_4; N_2O = 298 kg CO_2e/kg N_2O; Myhre et al., 2013) were used to convert the estimated GHG emissions of the cropping systems into the common unit of kilograms of carbon dioxide equivalents (CO_2e). The results of this analysis are presented on an area basis (i.e., kg CO_2e/ha) and on grain yield basis (i.e., kg CO_2e/t). Ideally, the GHG emissions from producing the grain would be considered on a unit basis that better reflects the end-use of the grain (e.g., for human consumption); however, cereal, oilseed, and pulse grains are nutritionally non-equivalent. For example, oilseed grains are primarily consumed for their oil content, while pulses and cereals are consumed primarily as sources of protein and fibre. To date, a functional unit that properly accounts for these differences has not been established in the literature. Therefore, the carbon footprints in this study were determined on an area and yield basis (i.e., on a GHG intensity basis).

2.4.6. *Determining the total carbon footprint of cropping systems*

Emissions estimates from the production and acquisition of cropping inputs, on-farm fuel use, and managed soils, in combination with the statistically significant differences to yield and N fertilizer applications for each crop in each rotation and scenario determined in the meta-analysis were combined to estimate the carbon footprint (i.e., GHG emission intensities) of each crop in each pulse-free and pulse-containing rotation. The results of this study are presented for each individual crop under each scenario to allow flexibility for crops to be combined into a number of different pulse-containing and associated pulse-free reference rotations for comparison.

2.5. *Carbon footprint uncertainty analysis*

The uncertainty of the carbon footprint of each crop was examined by first determining the uncertainty of each element included in the carbon footprint, namely: pesticide application rates and emissions factors; GHG emissions from field operations; yield increases; and N_2O emission rates for each crop and scenario. These elemental uncertainties can be non-normal. For each crop in each rotation, these elements and their associated uncertainties were compiled into a model using the life cycle assessment software package SimaPro v8.3 (Pré, 2016). In SimaPro, the uncertainty of each element (e.g., pesticide application rate) was defined as a probability distribution. These probability distributions were based on a statistical analysis of data from the systematic review and meta-analysis including: 1) The standard deviation of pesticide application rates and emissions from field operations; 2) The standard error of the mean yield increase in each scenario; and 3) Uncertainties encoded in the DataSmart LCI for fertilizer emission factors.

It is important to note that data used to estimate N_2O emissions were from multiple sources with varying levels of detail regarding uncertainty. The uncertainty ranges provided in the literature ranged from +/− 25% to ± 50% (De Klein et al., 2006; Janzen et al., 2003; Rochette et al., 2008) and based on these values, the N_2O emissions parameter in the SimaPro model was assigned a normal distribution with a 95% confidence interval of ± 50%.

Due to the complexity of the crop rotation models and the associated uncertainty in each crop production element, Monte Carlo simulation in SimaPro as described by Weidema et al. (2013) was used to determine the aggregated uncertainty of each crop in the pulse-containing and pulse-free cropping systems. The simulation took into account the dependence/independence of each elemental uncertainty. For example, although the GHG emission intensity of fertilizer may vary, a test and reference crop that are treated with the same type of fertilizer should use the same emission factor. Models for each crop were developed to account for the dependence/independence of each elemental uncertainty.

The benefit of the approach used for the uncertainty analysis was that it allowed for the calculation of 95% confidence intervals for the carbon footprint of each crop in each rotation and scenario. This approach also allowed for a direct comparison between pulse-free and pulse-containing rotations in the example two-year crop rotation analysis discussed in Section 4.2.

3. Results

3.1. Systematic literature review and meta-analysis

Thirty-two papers were identified as meeting the criteria of the systematic literature review. From these papers, data on crop yield, grain protein content, N fertilizer application rates, SOC, and crop production energy inputs and GHG emissions were extracted and compiled. Of these 32 papers, 26 were found to report data in formats that permitted the analysis described in this study. The remaining six studies were excluded from the analysis (Lemke et al., 1999; Malhi et al., 2012; Miller et al., 2003a; Miller et al., 2002; Soon and Arshad, 2004; and Stevenson et al., 1998). The 26 papers included in the analysis are summarized in Table 1. Care was taken not to double-count field data that were reported across multiple studies.

For the meta-analysis, data from each pulse-containing rotation was compared to each pulse-free reference rotation within the same study that shared a location and cropping year. This resulted in over 1900 comparisons from the 26 studies. Only three of the 26 studies that provided data to the meta-analysis portion of the study reported crop production data over a period greater than ten years; therefore, the extracted data were biased toward short-term (< 10 years) cropping systems.

Yields of cereal or oilseed crops grown after dry pea did not differ significantly when compared to cereal or oilseed crops grown after lentil (*p*-values of 0.1–0.9 in two-tailed *t*-Test). Thus, the data for crops grown subsequent to either pea or lentil were combined to reflect crops grown after 'pulse' crops. Aggregating the data in this way allowed for a more robust analysis as limited data were available for each rotation in each scenario. Results of the meta-analysis demonstrating differences in yield (N_N and N_{CR}) and N requirements to maintain yield (N_{CR}) in the pulse-containing rotations compared to the reference pulse-free rotations are summarized in Table 2.

In the N_N scenario, yield increases were observed when pulse crops were introduced into the reference rotations; C—C (+16%), C—O (+6%), O—C (+7%), and O—O (+7%). Mean yield increases for each reference rotation were significant at $P < 0.05$ except for C—O. Table 2 also shows the grain protein content of cereals grown after a pulse compared to those grown after a cereal or oilseed for N_N; however, data were not available for conducting similar analysis for the N_{CR} scenario. The protein content of cereal grains increased an average of 1.3% when grown after a pulse compared to after a cereal in N_N. The changes in protein content for the other rotations were not significantly different from zero. Given that changes to protein content were not able to be quantified for N_{CR} and were found to be zero for rotations other than C—C vs P—C, improvements or detriments to grain quality were not considered in the carbon footprints in this analysis. In the case that additional data become available and changes to grain quality in oilseeds or cereals in N_{CR} can be better estimated, a protein-corrected (or equivalent metric for oilseeds) yield can be applied to the carbon footprints to better estimate the effects of changes to grain quality on GHG emissions from crop production.

In the N_{CR} scenario, the results of the meta-analysis indicated that cereals grown after pulses and with reduced synthetic N fertilizer rates were able to maintain equivalent yields to their well-fertilized monoculture counterparts. For O—C (P—C) and O—O (P—O) rotations, 30 kg N/ha reductions were determined to be feasible. For C—O, the average yield of the oilseed grown after dry pea or lentil was not statistically significant compared to when grown after a cereal. Furthermore, the oilseed yield was not maintained when N fertilizer rates were reduced. Therefore, for the C—O reference rotation, the effects of preceding oilseeds with dry peas or lentils in a two-year rotation were similar for the N_{CR} and N_N scenarios.

The effects on SOC from the inclusion of pulse crops into annual cropping rotations demonstrated considerable variability. As such, the effects of pulse crops on SOC were not able to be quantified and were therefore excluded from the analysis. In the case that additional information becomes available and it is determined that pulse crops affect the SOC levels of annual cropping systems, these impacts (positive or negative) should be considered in combination with the N and yield benefits that pulses offer to the rotation. Additional research on this topic would be beneficial to the development of long-term management strategies for reducing the GHG emissions from cropping systems.

3.2. Carbon footprints of individual cereal and oilseed crops grown in either pulse-containing or pulse-free cropping systems

Table 3 shows the GHG emissions from producing dry pea and lentil, as well as cereal and oilseeds as second year crops in the rotations of interest for pulse-free reference rotations and pulse-containing rotations. The emissions are presented on an area (per ha) and yield (per tonne of grain produced) basis for both the N_N and N_{CR} scenarios.

In general, cereal and oilseed crops grown after a pulse crop had similar or reduced GHG emissions compared to those grown after a cereal or oilseed (Table 3). The GHG emissions from individual crops in the pulse-containing rotations were higher in N_N (888–987 kg CO_2e/ha; 286–598 kg CO_2e/t) than in N_{CR} (311–978 kg CO_2e/ha; 116–598 kg CO_2e/t), suggesting emissions were reduced to a greater extent when pulse crops offset the N fertilizer requirements of a subsequent crop compared to when they were used to provide additional N in order to maximize crop yields. The high level of uncertainty in the P—O vs C—O comparison prevented the statistical determination of whether a reduction in synthetic N fertilizer was possible as a result of including pulses in the rotation.

4. Discussion

4.1. Greenhouse gas emissions from individual crops within rotations

In the pulse-free reference rotations, oilseed crops were found to have the largest carbon footprint (988 kg CO_2e/ha and 640 kg CO_2e/t; Table 3) as a result of lower yields (1542 kg) compared to cereals (2671 kg) and dry peas (2132 kg), as well as increased N requirements

Table 1
Literature identified by the systematic review as relevant to the goal of the analysis, and details on the data extracted from each study.

Reference	Pulse-free reference rotation(s)	Province of field studies	Date range of study	Scenario (N_N or N_{CR})	Data extracted from studies					
					Yield	Protein[a]	N fertilizer	SOC	Energy input	GHG
Dry Peas										
Beckie and Brandt, 1997	C-C; O-C; O-O; C-O	SK	1993–1995	N_N/N_{CR}	x		x			
Bremer et al., 2008	C-C; O-C; F-W	SK	1992–2003	N/A				x		
Lupwayi and Soon, 2009	C-C	AB	2002–2004	N_N	x	x	x			
Miller et al., 2003b	C-C; O-C; O-O; C-O	SK	1996–1999	N_N/N_{CR}	x	x	x			
Soon and Clayton, 2002	C-C	AB	1993–2000	N_N	x		x			
Soon and Clayton, 2003	C-C	AB	1993–2000	N_N	x	x	x			
Soon and Lupwayi, 2008	C-C	AB	2002–2004	N_N	x	x	x			
Soon et al., 2004	C-C; O-C	AB	1997–1999	N_N	x	x	x			
Stevenson and Van Kessel, 1996	C-C	SK	1993–1994	N_N/N_{CR}	x	x	x			
Turkington et al., 2012	C-C; O-C	AB/SK	2006–2009	N_N	x	x	x			
Zentner et al., 2004	C-C	SK	1987–1998	N_N/N_{CR}					x	
Lentils										
Bremer and Van Kessel, 1992	C-C	SK	1988–1989	N/A			x			
Bremer et al., 2011	C-C	AB/SK	1992–2009	N_N/N_{CR}	x	x	x	x		x
Campbell et al., 1992	C-C	SK	1979–1990	N_N/N_{CR}	x	x	x			
Campbell et al., 2000	C-C	SK	1967–1996	N/A				x		
Congreves et al., 2015	C-C	SK	1967–2009	N/A				x		
Dry Peas and Lentils										
Gan et al., 2011a	C-C; O-C; O-O; C-O	AB/SK/MB	N/A	N_N/N_{CR}						x
Gan et al., 2011b	C-C; O-C; O-O; C-O	SK	1996–2000	N_N/N_{CR}						x
Khakbazan et al., 2016	C-C; C-O	AB/SK/MB	2009–2011	N_N/N_{CR}					x	
Lemke et al., 2007	C-C	NGP	1994–2005	N/A				x		
Luce et al., 2015	C-C; O-C; O-O; C-O	AB/SK/MB	2010–2011	N_N/N_{CR}	x		x			
MacWilliam et al., 2014	C-C	AB/SK/MB	1989–2008	N/A	x	x	x			x
Rochette and Janzen, 2005	N/A	AB/SK	N/A	N/A			x			x
Wright, 1990a	C-C	SK	1983–1986	N_N/N_{CR}		x	x			
Wright, 1990b	C-C	SK	1983–1986	N_N/N_{CR}	x	x	x			
Zentner et al., 2001	C-C	SK	1979–1997	N_N	x	x	x			

Abbreviations: C = cereal; O = oilseed; AB = Alberta; SK = Saskatchewan; MB = Manitoba; N = nitrogen; N_N = no change in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop; N_{CR} = maximum reduction possible in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop, without affecting productivity; SOC = soil organic carbon; GHG = greenhouse gas emissions; N/A = not applicable (e.g., data on energy inputs may not be specific to a scenario).

[a] Grain protein content collected for cereal crops only. Includes studies reporting grain protein content and grain nitrogen content (grain N content multiplied by 5.83 [Food and Agriculture Organization of the United Nations, 2003] to estimate protein content).

(112 kg/ha) compared to cereals (86 kg/ha), dry peas (0 kg/ha), and lentils (0 kg/ha). Note that N fertilizer values provided here are specific to N-based fertilizers and pulse crops do receive synthetic nitrogen via the use of phosphorous fertilizers. Greenhouse gas emissions from cereal production produced almost half (52%) the emissions from oilseeds when considered on a yield basis due to the higher cereal yields, but only 11% lower when considered on an area basis. Dry peas were found to have a larger carbon footprint than lentils when considered on an area basis (402 kg CO_2e/ha compared to 268 kg CO_2e/ha), but lower when considered on a yield basis (188 kg CO_2e/t compared to 210 kg CO_2e/ha). The N_2O emissions from dry peas were roughly 150% greater than lentil due to greater crop yields (2132 kg compared to 1278 kg) and increased nitrogen content in above-ground biomass (0.018 kg N/kg dry matter) when compared to lentils (0.010 kg N/kg dry matter; Janzen et al., 2003). As a result of the increased N_2O emissions in dry peas compared to lentils, GHG emissions were higher per hectare for dry pea production. However, dry pea yields were found to be approximately 67% higher than lentil yields, thus resulting in lower GHG emissions per tonne of grain produced.

In the N_N scenario, when cereals were grown after pulses, the carbon footprint of the cereal crop was reduced by approximately 13% and 6% on a yield basis (Table 3) when compared to after a cereal or oilseed, respectively. This was due to the increases in cereal yields. Similar to cereals, oilseeds grown after pulses in the N_N scenario had reduced emissions per tonne (~7%) when compared to oilseeds grown after either cereals or oilseeds (Table 3). On an area basis, the carbon footprints of cereals or oilseeds grown after pulses in N_N were comparable to their pulse-free counterparts as management practices, in particular N fertilizer rates, were similar.

In the N_{CR} scenario, cereals grown after pulses reduced GHG emissions by 65% (area and yield basis) compared to when grown after a cereal, and approximately 25% (area and yield basis) compared to those grown after an oilseed. Greater reductions in GHG emissions occurred in P—C vs C—C than in P—C vs O—C primarily because N fertilizer was not required in the P—C rotation to maintain an equivalent cereal yield for C—C. Cereal yields in O—C (2,846 kg; Table 3) were higher than in C—C (2,705 kg; Table 3) and N fertilizer was therefore required by the cereal crop in order to maintain the higher yield. As a result, reductions in GHG emissions were not as great in O—C compared to C—C. Oilseed yields in P—O vs C—O were not able to be maintained when N fertilizer rates were reduced, which led to GHG emissions from these rotations in the N_{CR} scenario being similar to the N_N scenario. In P—O vs O—O, 20% (area and yield basis) reductions in GHG emissions occurred as a result of reducing N fertilizer application rates by 30 kg N/ha.

The results of this analysis indicated that the inclusion of pulse crops in otherwise pulse-free rotations was, in general, statically beneficial for reducing the total GHG emissions of cropping systems. Overall, pulses led to reduced N requirements and increased yields, except when oilseeds were grown after a pulse instead of a cereal crop. The protein content of a cereal crop significantly increased by 1.3% when grown after a pulse crop instead of a cereal or oilseed in N_N; however, the lack

Table 2
Results of meta-analysis showing relative changes to yield and protein content for scenario N_N and yield and synthetic nitrogen fertilizer requirements for scenario N_{CR} between pulse-free and pulse-containing cropping systems in Western Canada.

Parameter	Reference (Pulse-containing) Rotation[1]			
	C-C (P—C)	C-O (P—O)	O-C (P—C)	O-O (P—O)
	Scenario 1: N_N			
Mean of yield increase in C or O grown after P compared to after C or O (%)	16ł	6	7 ł	7 ł
SEM (%)	2.26	4.83	1.54	2.36
n	52	26	38	22
Protein in C in reference rotation (%)	14.5	N/A	14.3	N/A
Protein increase in C grown after P compared to after C or O (%)	1.34 ł	N/A	0.06	N/A
SEM (%)	0.21	N/A	0.35	N/A
n	21	N/A	7	N/A
	Scenario 2: N_{CR}			
Synthetic N applied to C or O after P compared to after C or O[2]	N fertilizer not required	No change from reference crop	30 kg N/ha reduction from reference crop	30 kg N/ha reduction from reference crop
Mean of yield increase in C or O grown after P compared to after C or O (%)	1	6	1	6
SEM	2.93	4.83	1.51	4.14
n	28	26	22	18

Abbreviations: SEM = standard error of mean; n = sample size (i.e., number of trial-by-trial comparisons); P = pulse (dry pea and lentil); C = cereal; O = oilseed; N = nitrogen; N_N = no change in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop; N_{CR} = maximum reduction possible in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop, without affecting productivity.

ł Mean is significantly different than zero at $P < 0.05$.

[1] Pulse-containing rotation to which reference crop is being compared is shown between parentheses.

[2] Refers specifically to N-based fertilizer rates and does not include the fraction of nitrogen that crops receive as a result of the applied P fertilizer.

of data for a similar analysis for the N_{CR} scenario meant increases to protein content could not be confirmed. GHG emissions were reduced to a greater extent when N was reduced as much as possible (N_{CR}) as opposed to opting for higher yields through the use of increased fertilizer rates (N_N).

It is important to note that the carbon footprints in this analysis were developed from data from the available literature and may, therefore, be subject to publication bias (i.e., positive results are more likely to be published). In addition, crop rotations are complex and have many interrelated factors that are not captured when focusing on GHG emissions, or when examining only one crop grown after a pulse crop. The authors attempted to quantify effects beyond one cropping year after a pulse crop; however, data were not available for such an analysis.

4.2. *Comparison of the greenhouse gas emissions from two-year pulse-containing and pulse-free cropping systems*

The total GHG emissions from individual crops shown in Table 3 can be combined into various reference rotations of interest and compared to similar pulse-containing rotations to determine the effects to GHG emissions from the inclusion of the pulse crop(s). To demonstrate the concept and to further investigate the results of the analysis, two-year crop sequences were examined (Fig. 1). The inclusion of pulse crops in two-year rotations reduced GHG emissions in all rotations and in both scenarios, with the exception of C—O vs P—O where the uncertainty in oilseed yields was too high to determine if a reduction in GHG emissions was within the 95% confidence interval. In the N_N scenario, reductions in GHG emissions ranged from 475 to 719 kg CO_2e/ha (area basis) and 164–496 kg CO_2e/t (yield basis) over the two-year rotations. In the N_{CR} scenario, emission reductions ranged from 489 to 1185 kg CO_2e/ha (area basis) and 335–610 kg CO_2e/t (yield basis) over the two-year period. In both scenarios, decreases in GHG from the inclusion of pulse crops were primarily due to lower requirements for N fertilizer across the entire rotation, particularly since dry pea and lentil did not require N fertilizer beyond the N available in phosphorous fertilizer.

Cereal crops were found to benefit more than oilseeds when grown after a pulse crop in terms of increased yields and reduced N requirements (Table 2; Fig. 1). However, reductions in GHG emissions in O—O vs P—O were comparable to rotations where pulses were grown before a cereal due to the substitution of a crop with a relatively high carbon footprint of production (i.e., oilseed) with a crop with a comparatively low carbon footprint of production (i.e., dry pea or lentil). Similar to the results for individual crops (Table 3), a decrease in applied synthetic N fertilizer over the entire rotation led to greater reductions in GHG emissions than when crops received increased N to maximize crop yields.

A two-year analysis was selected for the simplicity of demonstrating the above-mentioned concept; however, growing pulses in such close succession is not recommended due to the potential reduction in soil health and increase in crop diseases that are prevalent in low-diversity rotations (Bainard et al., 2017). In addition, Campbell et al., 1992 found that the inclusion of lentil every second year into a monoculture cereal rotation over a 30-year time period resulted in a gradual build-up of N in the soil over time, eventually leading to an excess in soil N. These factors may offset the GHG benefits of using pulses in crop rotations if: 1) Pulse crops preferentially use soil N over fixing their own N (Schoenau, 1996); 2) Crops require additional plant protection products to combat pests and disease; or 3) Additional efforts are required to counteract long-term soil health degradation.

4.3. *The broader implications of including pulse crops into cropping systems in western Canada*

The estimated carbon footprints from the different rotation systems can be used to contemplate some of the broader implications of the potential role for pulse crops in the development of improved cropping systems in western Canada. For example, in 2015, 51% of spring wheat was grown after an oilseed crop, 23% after another cereal, 19% after a pulse, 6% after summerfallow, and 2% after soybean (AAFC, 2017). Assuming a hypothetical situation where: 1) Pulse crops were not grown prior to the 2015 wheat crop; 2) A proportional increase of the pulse-free rotations had occurred; 3) Rotations were managed according to the results of the meta-analysis and soybeans were excluded; and 4) The results of the summerfallow rotations in the expanded NGP (Supplementary Materials) were representative of the western

Table 3
Greenhouse gas emissions per hectare and per tonne of grain produced for each crop in the pulse-free reference and relative pulse-containing rotations in western Canada. Total greenhouse gas emissions from individual crops from the reference rotations can be combined into any rotation of interest and compared to a related pulse-containing rotation to determine changes to greenhouse gas emissions.

Crop[1]	N fertilizer rate[2]	Ph fertilizer rate[2]	Yield[3]	Seed[4]	Pesticide[5]	N fertilizer[6]	Ph fertilizer[6]	Field operations[5]	N_2O[7]	Total GHG emissions (area basis)	95% confidence interval	Total GHG emissions (yield basis)	95% confidence interval
	Key inputs (kg N or P_2O_5 or grain ha^{-1})			Emissions on an area basis (kg CO_2e ha^{-1})								Emissions on a yield basis (kg CO_2e $tonne^{-1}$)	
Inputs and emissions for pea and lentil													
Pea	0	13	2132	37	35	0	22	114	194	402	286–518	188	134–243
Lentil	0	13	1278	20	35	0	22	114	77	268	213–338	210	167–265
Pulse-free reference rotations													
C-C	86	30	2671	38	39	300	49	119	337	882	693–1080	330	259–404
C-O	112	33	1542	3	39	371	53	119	402	988	764–1210	640	495–785
O-C	86	30	2671	38	39	300	49	119	337	882	694–1060	330	260–397
O-O	112	33	1542	3	39	371	53	119	402	988	764–1210	640	495–785
Pulse-containing rotations for comparison: Scenario 1 – Unadjusted N fertilization rates (N_N)													
P-C (C–C)	86	30	3103	38	35	300	49	114	352	888	704–1080	286	209–423
P-O (C–O)	112	33	1635	3	35	371	53	114	402	978	761–1190	598	374–1160
P-C (O–C)	86	30	2846	38	35	300	49	114	343	879	691–1060	309	229–415
P-O(O–O)	112	33	1654	3	35	371	53	114	411	987	750–1220	597	442–803
Pulse-containing rotations for comparison: Scenario 2 – Adjusted N fertilization rates (N_{CR})													
P-C (C–C)	0	30	2705	38	35	0	49	114	75	311	252–377	116	83–174
P-O (C–O)	112	33	1635	3	35	371	53	114	402	978	761–1190	598	374–1160
P-C (O–C)	56	30	2846	38	35	195	49	114	247	679	555–819	250	193–320
P-O(O–O)	82	33	1542	3	35	272	53	114	310	787	632–962	510	331–756

Abbreviations: C = cereal; O = oilseed; P = pulse; N = nitrogen; Ph = phosphorous; P_2O_5 = diphosphorus pentoxide; GHG = greenhouse gas; N_2O = nitrous oxide; N_N = no change in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop; N_{CR} = maximum reduction possible in synthetic N fertilizer applied to cropping system due to inclusion of pulse crop, without affecting productivity.

[1] Bold and underlined text = crop for which data are presented (single year of rotation); Non-bold text = preceding crop (for reference only, data presented do not include emission from preceding crop). Reference sequences are shown between parentheses.

[2] N and Ph fertilizer rates from Canada Field Print Initiative Fertilizer Use Surveys (2014/2015). N fertilizer rates for pulse-containing rotations in N_{CR} were adjusted based on the results of meta-analysis. Note that N fertilizer rate refers specifically to N-based fertilizers and does not include the fraction of nitrogen that crops receive as a result of the applied P fertilizer.

[3] Average annual yield from 1993 to 2011 (Statistics Canada, 2017). Average yields of crops following a pulse were adjusted based on results of meta-analysis.

[4] Seeding rates from Crop Planning Guide 2016 (Government of Saskatchewan, 2016) and emissions data derived from MacWilliam et al., 2014.

[5] From systematic review.

[6] N and Ph fertilizer include emissions from production, distribution, and use of fertilizer. N emission factors (C = 3.48 kg CO_2e/kg N; O = 3.31 kg CO_2e/kg N) developed from proportion of each type of N fertilizer (e.g., urea) applied to each crop (Canada Field Print Initiative, 2014 and 2015) and associated relevant emission factors from the DataSmart life cycle inventory (Long Trail Sustainability, 2016). Ph fertilizer emission factor (1.62 kg CO_2e/kg P_2O_5) from DataSmart (Long Trail Sustainability, 2016).

[7] N_2O emissions include direct and indirect N_2O emissions. Calculated using methodology described in IPCC (2006). Canadian-specific values for R_{AG}, N_{AG}, R_{BG}, and N_{BG} (Janzen et al., 2003) and the emission factor for N_2O-N (0.0048 kg N_2O-N kg^{-1} N^{-1}; Rochette et al., 2008) were substituted for IPCC default values.

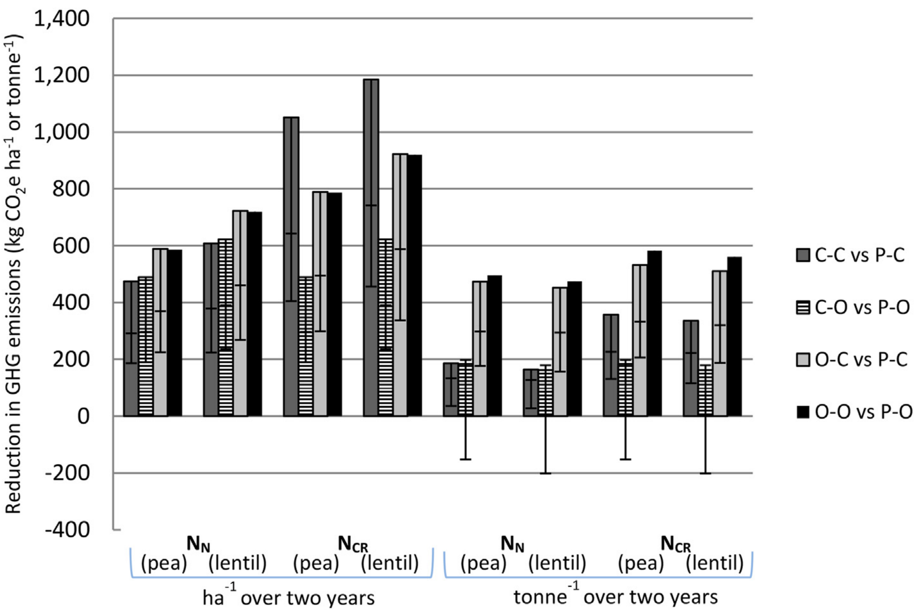

Fig. 1. Greenhouse gas emissions savings in two-year pulse-containing rotations compared to pulse-free rotations in Western Canada. Error bars denote 95% confidence interval. Emissions savings are significant where error bars do not extend below zero (i.e., all cases except O—C vs P—C). C = cereal; P = pulse; O = oilseed.

Canadian context, pulse crops would have reduced GHG by approximately 1.1 Mt. CO_2e (area basis) in western Canada over the two-year period under N_N conditions. In the case of N_{CR}, where the use of synthetic N would have been reduced as much as possible without negatively affecting crop yields, the inclusion of pulse crops would have saved roughly 1.5 Mt. CO_2e (area basis). Considering similar rotational data for spring wheat production in 2010 where 42% was grown after oilseed, 37% after cereal, 14% after pulse, and 7% after summerfallow, pulses would have reduced emissions by approximately 0.7 and 1.1 Mt. CO_2e (area basis) in N_N and N_{CR}, respectively. This translates to an estimated 0.4 (N_N) or 0.5 (N_{CR}) Mt. CO_2e (area basis) potential reduction in emissions from including an additional 5% of pulse crops into rotations. While this is an overly simplified examination of a real-world cropping system, it highlights the importance of diversifying crop rotations and the potential for pulses to reduce GHG emissions from cropping systems while maintaining or increasing system productivity.

5. Conclusions

Pulse crops, such as dry peas and lentils, can play a role in optimizing the management diversification of cropping systems due to their ability to reduce the synthetic N requirements of crop rotations while maintaining or improving productivity. The most effective way to reduce GHG emissions from crop production is to develop strategies where the emissions from GHG-intensive inputs, particularly synthetic N fertilizer, are reduced and crop yields are maintained or improved. The inclusion of dry peas and lentils into well-managed annual rotations is one such strategy to reduce the GHG emissions from cropping systems, and ultimately global food production systems.

Meta-analysis was used in this study to develop more powerful and precise estimates of the effects of pulse crops on rotational yield and N fertilizer requirements when pulses precede cereals and oilseeds in a cropping system. Results of this study demonstrate that the inclusion of pulse crops into pulse-free rotations is statistically beneficial for reducing GHG emissions. Reducing the N fertilizer rates of a crop rotation resulted in greater GHG emissions savings than when yields were maximized by maintaining fertilizer rates in pulse-containing rotations compared to pulse-free rotations. From the perspective of individual growers, it is likely that when socio-economic factors (beyond the scope of this analysis) are considered in combination with environmental factors, that the optimal balance between reducing fertilizer application and maximizing yields lies somewhere between the extremes of N_N and N_{CR}.

In general, pulse crops were more beneficial when preceding cereal crops compared to oilseed crops in terms of reducing N fertilizer requirements, improving crop yields, and potentially increasing the quality of the grain. However, pulse crops were found to be beneficial to oilseed-based rotations in terms of GHG reductions since pulse crops were not detrimental to oilseed yields or N requirements and had a comparatively low carbon footprint to oilseeds. As such, replacing the growth of a crop that has relatively high GHG emissions, such as an oilseed, with a crop with a relatively low carbon footprint, such as dry pea or lentil, is beneficial to the rotation.

To date, a functional unit that properly accounts for the complexities of examining changes to the GHG emissions of producing nutritionally non-equivalent products has not been fully realized. Given that principal crops in western Canada are grown for consumption, additional analysis on how best to incorporate pulse crops into annual cropping systems to maximize GHG reductions, as well as best support future global food requirements is warranted. Furthermore, effects to SOC and a full accounting of the effects of pulses on the N cycle of cropping systems would support more-informed crop production strategies. Further analysis should be conducted with consideration for the projected effects of climate change on crop production systems, such as increased variability in temperature and precipitation, extreme weather events, water scarcity, and incidence of pest and disease outbreaks (FAO, 2016b), in order to determine optimized strategies for including pulses in rotations under future conditions. The results of this study are presented by individual crops in a variety of scenarios to allow for flexibility in assembling crop rotations of interest for analysis, as well as for incorporating additional literature data as they become available.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.07.016.

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