Farming tactics to reduce the carbon footprint of crop cultivation in semiarid areas. A review

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Abstract The human population on the planet is estimated to reach 9 billion by 2050; this requires significant increase of food production to meet the demands. Intensified farming systems have been identified as a viable means to increase grain production. However, farming intensification requires more inputs such as fertilizers, pesticides, and fuels; all these emit greenhouse gases and have environmental consequences. An overwhelming question is: can farming practices be improved which enables yield increase with no cost to the environment? Here, we present seven key farming tactics that are proven to be effective in increasing grain production while lowering carbon footprint: (1) using diversified cropping systems can reduce the system's carbon footprint by 32 to 315 % compared with conventional monoculture systems; (2) improving N fertilizer use efficiency can lower the carbon footprints of field crops as N fertilizer applied to these crops contributed 36 to 52 % of the total emissions; (3) adopting intensified rotation with reduced

summerfallow can lower the carbon footprint by as much as 150 %, compared with a system that has high frequency of summerfallow; (4) enhancing soil carbon sequestration can reduce carbon footprint, as the emissions from crop inputs can be partly offset by carbon conversion from atmospheric CO₂ into plant biomass and ultimately sequestered into the soil; (5) using reduced tillage in combination with crop residue retention can increase soil organic carbon and reduce carbon footprints; (6) integrating key cropping practices can increase crop yield by 15 to 59 %, reduce emissions by 25 to 50 %, and lower the carbon footprint of cereal crops by 25 to 34 %; and (7) including N₂-fixing pulses in rotations can reduce the use of inorganic fertilizer, and lower carbon footprints. With the adoption of these improved farming tactics, one can optimize the system performance while reducing the carbon footprint of crop cultivation.

Keywords Biological N₂-fixation · Carbon sequestration · Crop intensification · Crop diversification · Legumes · Pulse · Greenhouse gas emission · Nitrogen use efficiency · No-till · Soil organic matter

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Contents

1. Introduction
2. Definition of carbon footprint
3. Main factors contributing to the carbon footprint of field crops
 - 3.1. Crop residue decomposition
 - 3.2. Inorganic N fertilizer used in crop production
 - 3.3. Fossil fuels
 - 3.4. Pesticide use
4. Modeling of the carbon footprint of field crops
5. Reducing fertilizer use and including N₂-fixing pulses to reduce carbon footprint
6. Diversifying crop rotations to reduce carbon footprint

- 6.1. Case study—diversified rotation systems lowered carbon footprint
- 7. Intensifying crop rotations with less summerfallowing to reduce carbon footprint
 - 7.1. Case study—reducing summerfallow frequencies lowers the carbon footprint
- 8. Enhancing soil carbon sequestration to reduce carbon footprint
- 9. Managing tillage practices to reduce carbon footprint
- 10. Integrating agronomical practices to reduce carbon footprint
 - 10.1. Case study on durum wheat
- 11. Environmental conditions and carbon footprint
- 12. Conclusion
- Acknowledgments
- References

1 Introduction

Human population on the planet is continuously growing and thus the global demand for food, feed, fiber, and fuel will increase continuously for at least another 40 years (Godfray et al. 2010). This places unprecedented requirements for agriculture to increase its grain production substantially to meet the demand. Expanding cropping areas by clearing more uncultivated lands to increase grain production is possible, but this approach often comes at the expense of reducing carbon stocks in natural vegetation and soils (Whitfield 2006). Converting carbon-rich forests or grasslands to croplands for grain production causes the rapid loss of carbon reserves on the planet (Lal 2004; Pan 2011), jeopardize ecosystem biodiversity (Isbell 2011; Godfray 2011a), and has significant environmental consequences (Godfray 2011b; Foley et al. 2011). Therefore, increases of grain production must rely mostly on existing croplands rather than clearing new lands for farming (West et al. 2010).

There is a huge gap between the present level of crop yields and yield potential (Mueller et al. 2012), and this yield gap could be narrowed or even closed, at least on those underperforming farmlands. Success of achieving this goal depends on the use of improved agronomical practices (Gan et al. 2014), the enhancement of resource use efficiencies (Fedoroff et al. 2010), and the adoption of new farming approaches (Chai et al. 2014; Hu et al. 2015). However, farming has significant environmental consequences. In particular, increased use of inorganic fertilizers and pesticides in high-yielding farming systems increases carbon emissions (Dusenbury et al. 2008; Guo et al. 2010), as most crop production inputs serve as the major sources of greenhouse gas emissions (Burney et al. 2010; Goglio et al. 2014). Also, application rates of inorganic fertilizers and pesticides may accelerate the degradation of farmland

(Guo et al. 2010), making farming unsustainable for the long term (Fumagalli et al. 2011). More importantly, the general public is becoming more aware and concerned about the effect of farming on environmental sustainability and society health as a whole (West et al. 2013). In this review, we present some of the key agronomical tactics that can be employed to increase crop productivity and narrow the yield gap while at the same time, lowering the environmental impacts of farming.

2 Definition of carbon footprint

Greenhouse gas emissions are one of the key indicators in assessing the environmental sustainability of farming (Gómez-Limón and Sanchez-Fernandez 2010). To quantify the impacts, we define and use the term carbon footprint using the two metrics throughout the article: (a) the total amount of greenhouse gas emissions per unit of farmland—quantifying the total amount of emissions in crop production that focuses more on environmental health and (b) the quantity of greenhouse gas emissions associated with per kilogram of grain produced—emphasizing both emissions during the production of a crop as well as the products (i.e., grain yield) associated with per unit of emission. The latter focuses on increasing crop yield while reducing the greenhouse gas emissions. These are the most commonly used terminology in the full “Life-Cycle-Assessment” (i.e., LCA) analysis for quantifying the impact of farming activity on the environment.

3 Main factors contributing to the carbon footprint of field crops

There are many factors that contribute to the greenhouse gas emissions associated with the production of a field crop. In the full LCA analysis, it includes CO₂ emissions from off-farm manufacture, transportation, and delivery of various input products to the farm gate as well as those emissions during the cultivation of a crop (Fig. 1). Emissions from field crop production are mostly derived from (1) crop residue decomposition; (2) inorganic fertilizers applied on farm to the crop; (3) manufacture, storage, and transportation of inorganic N and P fertilizers, herbicides, and pesticides to the farm gate; (4) various farming operations such as spraying pesticides, planting and harvesting the crop, and tillage operations; (5) soil carbon gains or losses from various cropping systems; and (6) emissions of N₂O from summerfallow areas where the land is prepared for the crop to be grown the following years. The system boundary is usually set from cradle-to-farm gate. Below are more detailed descriptions for the major emission-contributing factors.

Fig. 1 The major contributors to greenhouse gas emissions in crop production include the emissions associated with off-farm manufacture, transportation, and delivery of input products to the farm gate and the emissions during the crop growth period and after harvest. In the calculation, the boundaries are set for a full “Life-Cycle-Assessment” analysis

3.1 Crop residue decomposition

Crop straw is normally left on the soil surface under no-till management or is incorporated into the soil through tillage after a field crop is harvested for grain or feed. The crop residue serves as an important N source in the soil for nitrification and denitrification, contributing directly and indirectly to N_2O emissions (Forster et al. 2007). The amount of emissions from the decomposition of the straw and roots depends on the net productivity of the crop, N concentrations of the plant matter (Janzen et al. 2003), environmental conditions such as soil moisture and temperature (Lal 2011; Flynn et al. 2005), and the duration from spring thaw to fall freeze up (Rochette et al. 2008). Studies in southern Saskatchewan, Canada, show that a large portion (25 %) of the total emissions is attributed to the decomposition of straw and roots for a cereal crop, such as durum wheat (*Triticum durum* L.) produced on the semiarid northern Great Plains (Gan et al. 2011). In the production of grain crops, the carbon footprint can be reduced by effective management of straw and roots, by adopting, for example, the improved production practices such as no-till cropping.

3.2 Inorganic N fertilizer used in crop production

Using the methodology of the Intergovernmental Panel on Climate Change (IPCC 2006) adapted for Canadian conditions (Rochette et al. 2008), synthetic N fertilizers used in the production of a cereal crop contributed the greatest percentage of the carbon footprint, averaging 65 % of the total emissions (Gan et al. 2011). The total emission included direct and indirect emissions through volatilization of NH_3 and NO_x ,

leaching of nitrate from the application of N fertilizers on farm fields (27 % of the total emissions), and emissions associated with the production, transportation, storage, and delivery of N fertilizers to the farm gate (38 %). The intensity of the emissions associated with N fertilization depends on the ratio of precipitation to potential evapotranspiration during the period when the N fertilizer is applied (Gregorich et al. 2005). Direct and leaching emissions of N_2O due to the use of N fertilizers are proportional to the ratio of precipitation to potential evapotranspiration (Rochette et al. 2008). In western Canada, for example, the carbon footprint of spring wheat is estimated at $0.383 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain produced in the semiarid brown soil zone, which was 32 % lower than the carbon footprint ($0.533 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain) of the same wheat crop produced in the more humid black soil zone (Gan et al. 2011). The main contributor to the large difference in the spring wheat carbon footprint between the two soil zones was precipitation and the amount of fertilizer applied to the crop.

3.3 Fossil fuels

Modern agriculture largely owes its successes to an abundant supply of fossil fuels, which are essential for synthetic fertilizer production, transportation, storage, and delivery to the farm gate, as well as for various farm operations including seeding, fertilizer and pesticide applications, and harvesting of field crops. In general, the emissions from the industrial processes of synthesizing N fertilizers using fossil fuels prior to on-farm use far surpasses the emissions from pesticide production and application to field crops. Given the finite nature of fossil fuel reserves and the macro-scale environmental

impacts of consuming the fossil energy that underpins intensive agriculture, closer attention should be paid to the adoption of improved N fertilizer management in the production of high N response crops such as wheat and oilseeds in order to lower carbon emissions in crop production.

3.4 Pesticide use

Herbicides remain the most commonly used weed management practice in the production of field crops in most agricultural regions on the planet (Beckie 2007). In many cases, fungicides and insecticides are also used in the production of field crops. Each pesticide may have different emission intensity; however, at the present time, emissions for each individual pesticide used in crop production are not readily available. Researchers often assume that the emission factors are similar among products within a similar category, but there is a large difference between crop types in the amount of pesticide used during a given growing season. For example, the contribution to the carbon footprint by the use of pesticides in durum production on the Canadian prairie is often less than those reported in the production of *Brassica napus* canola or annual pulse crops (Gan et al. 2011). More pesticides are usually required in the production of oilseeds and pulses because severe disease pressure occurs more often in these broad-leaf crops than in cereal crops.

4 Modeling of the carbon footprint of field crops

The specific amounts of greenhouse gas emissions in crop production can be measured from field plots or in controlled environment chambers or growth rooms. These emission measurements can be used to examine how cropping treatments may affect emissions (Lemke et al. 2010). However, simulation models provide a more accurate estimate of emissions from large regions (Smith et al. 2014; Yang et al. 2014). With modeling approaches, site-specific data can be coupled with empirical data. In the scientific literature, there is a multitude of approaches to model N₂O, but one of the widely accepted modeling approaches is using emission factors for the key variables that cause N₂O emissions (Rochette et al. 2008). The amount of direct and indirect N₂O emissions is related to the quantity of N applied to the crop and to environmental conditions (Gregorich et al. 2005). At a given location or site, N₂O emissions from N fertilizers are far greater than emissions from any other source. Also, environmental conditions significantly affect the magnitude of the emissions. Total emissions of N₂O from inorganic N applications include the direct emissions from the inorganic N fertilizer and indirectly by transformation processes that occur during and

after crop production, such as leaching of N out of the rooting zone and volatilization of inorganic N (IPCC 2006). As well, the N contained in the crop residue after harvest provides an additional source of N for nitrification and denitrification during the decomposition of above- and belowground crop residue biomass resulting in N₂O emissions from the soil (Gan et al. 2009).

Summerfallow has been used in the production of field crops in many arid and semiarid regions of the world, such as Southwest Australia (Hunt et al. 2013), Northwest China (Hou et al. 2012), northern Eurasia (Takata et al. 2008), central Africa (Thilakarathna and Raizada 2015), and the northern Great Plains of North America (Zentner et al. 2007). During the summerfallow period, no fertilizer is applied; however, several other factors may stimulate N₂O emissions, such as higher soil water content, temperature, and available carbon and N in the soil. Field studies have shown that N₂O emissions during the summerfallow period are proportional to the emission from continuously cropped fields (Rochette et al. 2008). Gan et al. (2012a) developed an equation to estimate the effect of summerfallow on N₂O emissions.

Using available data from studies conducted in North America, we estimated emissions from the manufacture, transportation, storage, and delivery of fertilizers to the farm gate using emission factors of 4.8 kg CO₂ eq kg⁻¹ of N and 0.73 kg CO₂ eq kg⁻¹ of P₂O₅, multiplied by the amount of N and P fertilizers applied on a per hectare basis (Gan et al. 2012a).

There are large variations in emission factors for pesticide use in crop production, varying with crop species, pesticide products, and other relevant factors involved in the manufacture, transportation, and delivery of the pesticides to the farm gate. For studies conducted in Saskatchewan, Canada, the emissions by pesticides were estimated using emission factors of 23.1 kg CO₂ eq kg⁻¹ of active ingredient for herbicides and 14.3 kg CO₂ eq kg⁻¹ of active ingredient for fungicides (Gan et al. 2012b). The emissions associated with various farming operations such as tillage, planting, spraying, and harvesting were estimated using factors of 14, 14, 5, and 37 kg CO₂ eq ha⁻¹, respectively.

In general, the carbon footprint for a crop rotation system is calculated based on an entire rotation cycle, including all phases of the rotation, with and without consideration of the changes in soil organic carbon as;

$$CF = \left(\sum_i \sum_j \left(\text{Emission Category}_{i,j} + \Delta C \right) \right) / \sum_i \text{Grain Yield}_i$$

where, CF is the carbon footprint of a rotation system (kg CO₂ eq kg⁻¹ of grain), emission category_{i,j} is emissions from a *j*th emission category in an *i*th rotation phase (kg CO₂ eq ha⁻¹), grain yield_i is the grain yield of a crop from an *i*th phase of a rotation (kg ha⁻¹), and ΔC is the amount of change in soil organic carbon (kg C ha⁻¹ year⁻¹) when this factor is included in the footprint calculation.

Fig. 2 Increasing the rate of inorganic N fertilizer application to the crops increased (a) the CO₂ emissions from crop production resulting in a linear increase of the carbon footprint of the oilseed regardless of the crop species (b)

5 Reducing fertilizer use and including N₂-fixing pulses to reduce carbon footprint

Nitrogen fertilizer is the main crop input in the production of non-pulse crops, such as *B. napus* canola, *Sinapis alba* mustard, durum wheat, and barley (*Hordeum vulgare* L.). In oilseed production on the Canadian prairie, for example, increasing rates of N fertilizer has been shown to increase greenhouse gas emissions (Fig. 2a) and the carbon footprint (Fig. 2b). The emissions and the carbon footprint both are a linear function of the rate of N fertilizer applied to the oilseed crops, although the slope of the linear regression varied with crop species. Similarly, N fertilizer is the main contributor to greenhouse gas emissions in cereal production. In durum wheat production, the greenhouse gas emission from the N fertilizer application averaged 223 kg CO₂ eq ha⁻¹, which was more than 16 times the emissions associated with the various farming operations. Furthermore, the emissions and carbon footprint of cereal crops were significantly influenced by the rate of N fertilizer applied to the previous crops in the rotation (Fig. 3). Greater greenhouse gas emissions from the barley crop occurred as more N fertilizer was applied to the oilseed crops grown the previous year. In other words, the total emission in the production of the barley crop was a function of the rate of fertilizer N applied to the previous oilseeds. The amount of residual mineral N measured prior to seeding barley increased as the amount of N applied to the previous oilseeds

was increased above 90 kg N ha⁻¹. The trend of the effect was similar between two contrasting environments (Fig. 3a, comparing the wetter Indian Head with the drier Swift Current) or among oilseed species (Fig. 3b). A meta-analysis from 14 different field sites in European shows that the risk of high yield-scaled N₂O emissions in oilseed increases after a critical N surplus (Walter et al. 2015). The N₂O emissions can be especially higher in oilseed (as compared with cereals) after harvest due to the higher N contents in oilseed plant residues.

Including N₂-fixing pulse crops in a crop rotation can significantly decrease greenhouse gas emissions and the carbon footprint of the crop grown the following year (Fig. 4). The emissions from the application of N fertilizer averaged 251 kg CO₂ eq ha⁻¹ for durum wheat produced in cereal-durum, or oilseed-durum, whereas the durum wheat produced in the pulse-durum system emitted 162 CO₂ eq ha⁻¹ or 37 % lower than the durum wheat produced in the cereal- or oilseed-durum system (Gan et al. 2011). As a result, the carbon footprint of durum wheat produced in the cereal-durum crop rotation had an average carbon footprint of 0.42 kg CO₂ eq kg⁻¹ of grain. The carbon footprint of durum wheat preceded by a pulse crop, such as chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medikus), or dry pea (*Pisum sativum* L.) the previous year, was lowered to 0.30 kg CO₂ eq kg⁻¹ of grain or 28 % lower than when durum wheat was preceded by a cereal crop.

Fig. 3 The amount of residual mineral N in the soil is a function of the quantity of fertilizer N applied to the crops grown in the previous year. The magnitude of the effect varied with (A) the experimental sites (the wetter Indian Head versus the drier Swift Current) and (B) among the crops (flax, canola, and Sunflower) grown in the previous year in the rotation

Fig. 4 The carbon footprint of durum wheat was significantly lower when the crop was preceded by a pulse crop such as chickpea, dry pea, or lentil, compared with when preceded by a non-pulse crop in the crop rotation. This trend was similar across the brown, dark brown, and black soil zones (the three major soil zones) on the Canadian prairie

Furthermore, crops grown in the previous 2 years had a significant influence on the carbon footprint of durum wheat. An oilseed and a pulse crop alternately grown the previous 2 years (pulse-oilseed-durum, oilseed-pulse-durum, or oilseed-oilseed-durum systems) lowered the carbon footprint of durum wheat by 25 % compared with durum wheat grown in cereal-cereal-durum system. Durum wheat produced in a pulse-pulse-durum system had the lowest carbon footprint, at 0.27 kg CO₂ eq kg⁻¹ of grain, or 34 % lower than when the durum wheat was preceded by cereal crops the previous 2 years.

These studies clearly demonstrate that the emissions and the carbon footprint of cereals and oilseed crops is a function of N fertilizer applied to the crops. The decreased use of N fertilization lowers the carbon footprint accordingly. Also, increased N fertilizer application to the crops grown the previous years will increase the total emission of the subsequent crops as a greater amount of soil residue N causes more greenhouse gas emissions. However, the emission intensity can be substantially reduced by including N₂-fixing pulse crops in a crop rotation. The inclusion of pulses in the rotation allows the system to rely on the symbiotic N₂ fixation from the atmosphere, which significantly decreases the use of synthetic N fertilizer, thus lowering the carbon footprint.

6 Diversifying crop rotations to reduce carbon footprint

Crop diversification has become increasingly important in many parts of the world (Fig. 5) as a means to control problem weeds (Harker et al. 2009; Menalled et al. 2001), suppress plant diseases (Kutcher et al. 2013), increase production sustainability (Mhango et al. 2013), and enhance economics

(Zentner et al. 2002). Also, crop diversification has been considered a key cropping practice for improving agroecosystem productivity (Gan et al. 2015) and lowering the carbon footprint (Yang et al. 2014; Minx et al. 2009). We use a case study to describe the environmental benefits of using diversified systems in the production of field crops.

6.1 Case study—diversified rotation systems lowered carbon footprint

A well-managed field experiment was conducted at the Agroecosystem Station of the Chinese Academy of Science (37° 50' N, 114° 40' E), in Luancheng, Hebei Province, China. The experimental site was on the northern China Plains (Yang et al. 2014). The experiment, run from 2003 to 2010, included five cropping systems (Table 1): (1) winter wheat/summer maize (*Zea mays* L.) (2-year cycle), (2) peanut (*Arachis hypogaea* L.)/winter wheat/summer maize (3-year cycle), (3) rye (*Secale cereal* L.)/cotton (*Gossypium hirsutum* L.)/peanut/winter wheat/summer maize (5-year cycle), (4) sweet potato (*Ipomoea batatas* L.)/cotton/sweet potato/winter wheat/summer maize (5-year cycle), and (5) continuous cotton cropping. Each rotation was cycled on its assigned plots 30 × 7.5 m. Researchers found that the total emissions per unit of land varied significantly among the five cropping systems. Because of the different crops with different types of crop yield, the authors used biomass as the functional unit in the calculation of the carbon footprint of the various rotations. Based on biomass, the diversified 5-year rotation which included sweet potato—sweet potato/cotton/sweet potato/winter wheat/summer maize had the lowest carbon footprint at 0.24 kg CO₂ eq kg⁻¹ year⁻¹ whereas the least diversified rotation—the 2-year rotation of winter wheat with summer maize had the largest footprint at 0.85 kg kg CO₂ eq kg⁻¹ year⁻¹. When the footprint was calculated by using economic values as the functional units, Yang et al. 2014 found that the 5-year rotation including sweet potato had the lowest economic footprint, 0.28 kg CO₂ eq ¥⁻¹ year⁻¹, while the 2-year rotation of winter wheat with summer maize had the highest economic footprint, 1.12 kg CO₂ eq ¥⁻¹ year⁻¹.

A major benefit in lowering the biomass-based footprint for the 5-year diversified rotation was the lack of N fertilizer and a preference for K fertilizer in sweet potato that decreased total carbon emissions. Also, the crop residue from potato, winter wheat and summer maize, and the fallen leaves of cotton, were beneficial in maintaining the soil organic carbon in the top 20-cm soil layer. Increased soil organic carbon offset the input-induced greenhouse gas emissions. Furthermore, the large biomass of sweet potato reduced the biomass-based footprint whereas the higher price of cotton and sweet potato relative to wheat and maize lowered the income-based footprints. In this case study, multiple metrics (biomass and income-

Fig. 5 Pulse crops are being used in the integrated cropping systems in the semiarid northern Great Plains, with **a** lentil being one of the major pulses, **b** usually the annual pulse is direct-seeded into the standing stubble from the previous cereal under no-till management, and **c** a large number of nodules are formed on the roots that fix N_2 from the atmosphere

based) were used to calculate the footprint of the different cropping systems when analyzing for environmental impacts.

This and other studies clearly demonstrate that diversifying cropping systems in the production of field crops can be

Table 1 Average greenhouse gas emission and the footprint of five cropping systems in the north China Plains, 2003–2010

Cropping system	Total emission (kg CO ₂ eq ha ⁻¹ year ⁻¹)	Biomass-based footprint (kg CO ₂ eq kg ⁻¹ year ⁻¹)	Income-based footprint (kg CO ₂ eq ¥ ⁻¹ year ⁻¹)
WS	11,800	0.85	1.12
PWS	8532	0.76	0.61
RCPWS	8324	0.68	0.60
SpCSpWS	3292	0.24	0.28
Cont C	5249	0.36	0.39

Data were adopted from a published report (Yang et al. 2014)

W winter wheat, S summer maize, P peanut, R rye, Sp sweet potato, C cotton

effective in increasing total grain production at the system level with reduced carbon footprints. In designing a diverse cropping system targeted at lowering the footprint of the system, one must examine the overall greenhouse gas emissions and the footprint of individual crop species. Crops requiring low production inputs and those with a high yield of straw and roots for incorporation into the soil as carbon are keys to reducing the overall footprint of the system. However, the implementing diversified cropping systems to decrease greenhouse gas emissions in crop production must consider other factors. In the water-scarce Southeast Asian rice (*Oryza sativa* L.) production areas, changing the traditional double-rice cropping system to a more diversified system that included upland crops reduced irrigation water use in the dry season by about 70 % and decreased CH₄ emissions by 97 % without causing economic penalty (Weller et al. 2016). However, this system change resulted in a continuing loss of soil organic carbon and decreasing soil fertility (Weller et al. 2015). In Australian sugarcane (*Saccharum officinarum* L.) production, researchers found significant interactions among soil, climate, and cropping practices

that affect the magnitude of N_2O emissions (Thorburn et al. 2010). A study across the 30 provinces of China shows that the CO_2 emissions in agriculture was affected by changes in economic development, region-specific industrial structure, and investment and adaptation of new technologies far more than was affected by population density, energy structure, and resource availability (Tian et al. 2011).

7 Intensifying crop rotations with less summerfallowing to reduce carbon footprint

In arid and semiarid regions of the world, the productivity of agroecosystems is often constrained by a low availability of water and nutrients (Rasouli et al. 2014). One of the approaches employed to tackle these challenges is using summerfallow where the land is left unplanted for one growing season. For example, in the mid-1970s, approximately 11 million hectares of farmland were in summerfallow on the Canadian prairies, accounting for approximately 40 % of the total annual crop land of the region. The area of summerfallow has declined substantially in recent years, but still a large portion of the farmland is in summerfallow (FAOSTAT 2014). During summerfallow, a proportion of the rainfall is conserved in the soil profile (Tanaka and Aase 1987; Tanwar et al. 2014), which is then available for crops grown the following year (Sun et al. 2013). Additionally, summerfallowing encourages the release of N via the N mineralization of soil organic matter (Campbell et al. 2008), thus increasing soil N availability and helping to reduce the amount of inorganic N fertilizer used in cropping (Koutika et al. 2004). However, a number of studies have shown that the frequency of summerfallow in a cropping rotation has a significant impact on the carbon footprint of the rotation (Gan et al. 2012a; O'Dea et al. 2013; Schillinger and Young 2014). Crop intensification with reduced frequency of summerfallow in a rotation can increase crop production while reducing the carbon footprint. Below is a case study conducted in southwest Saskatchewan from 1985 to 2009 (Gan et al. 2012a), showing the environmental benefits of reducing the frequency of summerfallowing.

7.1 Case study—reducing summerfallow frequencies lowers the carbon footprint

A field experiment was initiated in 1966 at the Agriculture and Agri-Food Canada Research Centre at Swift Current ($50^\circ 17' \text{N}$, $107^\circ 48' \text{W}$). Detailed data on soil carbon were collected for the following four contrasting rotation systems in 25 years (1985–2009): (1) summerfallow-wheat, (2) fallow-wheat-wheat, (3) fallow-wheat-wheat-wheat-wheat, and (4) continuous wheat. The summerfallow frequency of these systems was taken as 50, 33, 17, and 0 %, respectively. All phases of each system were present every year, and each rotation was

cycled on its assigned plots. Each plot is 10.5 by 40 m. Overall, annualized wheat yields across the 25 study years were linearly proportional to growing season (1 May–31 Aug) precipitation; each millimeter of precipitation increasing grain yield by an average 5.26 kg ha^{-1} . Summerfallow frequency interacted with water availability in affecting grain yield. In the dry years, wheat in the fallow-wheat system had lowest annualized grain yield whereas wheat in the three other systems did not differ in yield, averaging 962 kg ha^{-1} . In normal to wetter years, annualized wheat yield differed significantly among the four rotation systems; with the continuous wheat system producing 9, 29, and 56 % more than wheat grain produced by the system that included 17, 33, and 50 % of the summerfallow phase in the rotation, respectively.

The grain yield of wheat grown on summerfallow was greater than the yield of wheat grown on stubble; this was largely due to more soil water conserved in the fallow fields under the semiarid environment (O'Dea et al. 2013). However, a higher frequency of summerfallow decreased the annualized yield of the system. The increased grain yield of the wheat crop grown after summerfallow, compared with wheat after wheat, did not overcome the lost opportunistic yield in the summerfallow phase (De Jong et al. 2008; Campbell et al. 2008).

As a result, wheat in the continuous wheat system produced the highest grain yield and gained highest soil organic carbon over the years, leading to the smallest footprint value at $-0.441 \text{ kg CO}_{2\text{e}} \text{ eq kg}^{-1}$ of grain, significantly lower than the footprint for the other three systems which ranged between -0.102 to $-0.116 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain (Fig. 6). The magnitude of the effects was influenced by water availability. In dry

Fig. 6 The carbon footprint of spring wheat is a function of fallow frequency and environmental condition. The footprint values change with and without soil organic carbon gain/loss included in the analysis. Line bars are standard errors. The four rotation systems are (1) continuous wheat (ContW), (2) fallow-wheat-wheat-wheat-wheat-wheat (FWWWWWW), (3) fallow-wheat-wheat (FWWW), and (4) fallow-wheat (FW). The summerfallow frequencies in the four rotation systems are 0, 17, 33, and 50 %, respectively

years, the carbon footprint averaged $-0.357 \text{ kg CO}_{2\text{b}} \text{ eq kg}^{-1}$ of grain compared with $-0.140 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain in normal years and $-0.093 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain in wet years. The highest negative carbon footprint in dry years is attributable to the lowest emissions from least N fertilization and least crop residue decomposition which more than offset the low grain yields. However, when soil carbon gains over the years were excluded, the carbon footprint differed little between the four systems. This case study shows that more intensified wheat cropping practices significantly increases soil carbon gains, increases annualized grain production, and thus lowers the carbon footprint.

A study of ten growing seasons in north-eastern Syria showed that the inclusion of pulses either as grain crops or hay in the rotation boosted profits considerably (Christiansen et al. 2015). Replacing summerfallow with common vetch (*Vicia sativa* L.) for hay production increased the average gross margin by US\$126 $\text{ha}^{-1} \text{ year}^{-1}$, and growing vetch for hay in rotation with wheat produced greater profit than continuous wheat, by \$254 $\text{ha}^{-1} \text{ year}^{-1}$. The wheat-vetch-for-grain and wheat-lentil rotations were twice as profitable as wheat fallow or continuous wheat. The benefits of replacing summerfallow with green manures in a rotation system may vary with climatic conditions and local farming practices. In a 2-year study at north-central Montana, replacing summerfallow with legume green manures in a rotation increased the average use efficiency of available N by 24 % during the wheat year and increased total residue carbon and N returned to soils by 260 and 26 kg ha^{-1} , respectively (O'Dea et al. 2013). However, overall wheat yield and protein content were reduced with the replacement of summerfallow with green manures. Previous manure crops may deplete soil water, causing yield reduction for the crops grown in the following years.

These studies clearly show that more intensified systems with reduced frequency of summerfallow in the rotation can reduce the system carbon footprint by as much as 250 %. In the Mediterranean-type climate, replacement of summerfallow with a forage or grain legume can more than double farming profits compared with the system with a high frequency of summerfallow. The benefits of replacing summerfallow with green manures in a rotation need to be further defined for regions with low water availability such as the US Montana plains.

8 Enhancing soil carbon sequestration to reduce carbon footprint

The Intergovernmental Panel on Climate Change has identified one of the main options for greenhouse gas mitigation in agriculture is the sequestration of carbon into soils (IPCC 2006). In North America and other areas on the planet, conversion of native prairie land for agricultural production has resulted in significant loss and redistribution of soil organic

matter in the soil profile ultimately leading to declining soil fertility in a low-productivity semiarid agroecosystem. It is estimated that the world's cultivated soils have lost 50 to 70 % of their original carbon stock, much of which has oxidized upon exposure to air to become CO_2 (Lal 2008). Some of those soils now represent a potential sink for CO_2 removal from the atmosphere (Hutchinson et al. 2007).

Soil carbon plays an important role in the estimate of the carbon footprint of a cropping system, because a per unit farmland greenhouse gas emission represents the balance between carbon-equivalent emissions and carbon sequestration in the production of a field crop. Inclusion or exclusion of soil carbon measurements can make a huge difference in the estimation of the carbon footprint (Gan et al. 2014). When the changes of soil organic carbon were excluded from the calculations, the four wheat-based cropping systems emitted an average of 642 $\text{kg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$ in wet years, 22 % more than was emitted in normal years and 110 % more than was emitted in dry years (Fig. 6). However, when soil organic carbon change was included in the calculations, the emission values became negative. The emissions associated with the crop production inputs were more than offset by the greater carbon conversion from atmospheric CO_2 into plant biomass and ultimately sequestered into the soil. Consequently, the net emissions per unit of farmland became negative.

Many crop/land management practices can be used to increase the amount of organic matter in the top soil and/or decrease decomposition rates, helping maintain soil structure and physical-chemical protection of soil organic carbon, improve soil carbon sequestration, and mitigate emissions to the atmosphere. For example, green manuring played a significant role in enhancing soil carbon levels in the summerfallow-cereal cropping system where relatively large increases in carbon inputs were achieved using currently available legume species (Curtin et al. 2000), increasing cropping frequency to reduce bare fallow was found to enhance soil carbon sequestration (Hurisso et al. 2013; Lefèvre et al. 2014; Gan et al. 2012a), including perennial forages, such as alfalfa (*Medicago sativa* L.) increased dryland soil carbon sequestration and biological soil quality by increasing microbial biomass and activity compared with annual cropping systems due to greater below-ground biomass carbon input and continuous root growth (Sainju and Lenssen 2011); using intensified intercropping with reduced tillage coupled with stubble mulching on the soil surface increased grain production while effectively lowering carbon emissions (Hu et al. 2015); reducing tillage intensity and frequency increased soil carbon (Sainju et al. 2010; Pinheiro et al. 2015) through carbon accumulation within the small macroaggregates and microaggregates at the 5–15-cm depth (Garcia-Franco et al. 2015), but this requires several decades to become distinguishable in this semiarid climate with small and variable carbon inputs (Shrestha et al. 2013). In addition, establishing agroforestry systems (i.e., the production of crops,

livestock, and tree biomass on the same area of land) by planting those high root biomass-to-aboveground biomass ratio and/or nitrogen-fixing trees can increase SOC sequestration effectively (Negash and Kanninen 2015). Detailed agroforestry management practices are needed to enhance carbon sequestration rates and the processes contributing to the stabilization of SOC in soil profiles.

Crop residues are a viable source for biofuel production and other industrial products; however, the removal of crop straw from agricultural land may negatively impact soil productivity and environmental quality (Smith et al. 2012). Proper fertilization is necessary to improve biomass conversion and thus increase residue returning to the soil (Zentner et al. 2011). However, the effect of fertilization on crop biomass and greenhouse gas emissions depends on environmental conditions. In the semiarid northern Great Plains of North America, fertilization of crops in medium-textured soils usually has little effect on emissions (Malhi et al. 2010), but significantly increases residue return back to the soil (Lemke et al. 2012).

These studies demonstrate that soil carbon sequestration plays a key role in reducing the carbon footprint of crop cultivation. Greenhouse gas emissions associated with the crop production inputs can be offset by greater carbon conversion from atmospheric CO₂ into plant biomass and ultimately sequestered into the soil. Appropriate land/soil management programs are required to optimize carbon conversion from the atmosphere while minimizing carbon loss in the production of crops.

9 Managing tillage practices to reduce carbon footprint

A number of studies have investigated how tillage practices may affect the carbon footprint and the published results are inconsistent, varying with climatic conditions, soil type, and cropping systems. In the tropical soils of Zimbabwe, a 9-year study found tillage and residue management significantly impacted soil organic carbon with conventional tillage having the least amount of organic carbon conserved in a Chromic Luvisol red clay soil (Chivenge et al. 2007). Tillage disturbance is the dominant factor reducing soil carbon stabilization within microaggregates in the clayey soil, whereas conservation practices increase soil organic carbon contents. In some cases, reduced tillage in combination with additional carbon input from cover crops significantly improved the soil organic carbon content (Garcia-Franco et al. 2015; Pinheiro et al. 2015). In a study conducted in a semiarid Mediterranean climate, reduced tillage with a mix of *V. sativa* L. and *Avena sativa* L. as green manure increased soil carbon content by 14 % in the 0–5-cm soil layer which was superior to other practices (Garcia-Franco et al. 2015). Plant residue inputs

from green manure and the incorporation into the soil by reduced tillage promoted the formation of new aggregates and activated the subsequent physical-chemical protection of organic carbon. In northwest China, wheat-maize intercropping under reduced tillage with stubble retention increased crop yield by 8 % and reduced greenhouse gas emissions by 7 % compared with conventional tillage (Hu et al. 2015).

However, soil organic carbon can be gained or lost depending on soil type and land use practices. Soil disturbance affects the quantity and quality of plant residues entering the soil, their seasonal and spatial distribution, and the ratio between above- and belowground inputs (Pinheiro et al. 2015; Sainju et al. 2010). Data from India show a linear relationship between carbon input and CO₂ output; an increase of 1 Tg CO₂ eq year⁻¹ of carbon input resulted in a corresponding increase in carbon output of 21 Tg CO₂ eq year⁻¹ (Maheswarappa et al. 2011). However, there is uncertainty about how tillage may affect soil organic carbon in some other areas. In a study conducted at eastern Montana, tillage did not influence crop biomass and CO₂ flux nor on total soil carbon content (Sainju et al. 2010). A study in southern Saskatchewan compared soil organic carbon amounts from 1995 to 2005 (Shrestha et al. 2013). After 11 years, soil organic carbon in the 0–15-cm depth was 0.2 Mg C ha⁻¹ higher under continuous cereal cropping compared with fallow-cereal systems. There were no significant differences in soil organic carbon content between minimal tillage and no-till practices. The study shows that soil organic carbon differences between tillage systems may require several decades to become distinguishable in this semiarid climate. Tillage may influence mineralizable carbon and microbial biomass (Campbell et al. 2005), but these effects do not necessarily increase soil available nutrients or crop yields (Campbell et al. 2011).

10 Integrating agronomical practices to reduce carbon footprint

Many studies have shown that integration of agronomic practices can substantially increase crop yields without increasing and sometimes decreasing greenhouse gas emissions. The integration may include, but is not limited to, optimizing fertilization in crop production without over- or under-fertilization so as to meet the nutrient requirement for optimal plant growth, using pulses to fix atmospheric N₂, and increasing crop residue input to the soil (Fig. 7). In this review, we discuss a well-managed case study below to describe these effects.

10.1 Case study on durum wheat

Cropping sequences in a rotation system have significant impacts on the carbon footprint (Gan et al. 2011). In the case

Fig. 7 Integrated farming practices are the key to reducing the carbon footprint of field crops. The key practices include optimizing fertilization to meet the nutrient requirement for plant growth, using pulse crops to fix atmospheric N_2 to partially replace inorganic N fertilizer, and increasing soil carbon input through crop residue management

study conducted in southern Saskatchewan, durum wheat had an average carbon footprint of $0.34 \text{ kg CO}_2 \text{ eq kg}^{-1}$ of grain when the crop was grown after canola or mustard, which was 19 % lower than when grown after a cereal (Table 2). Similarly, durum wheat grown after a chickpea, lentil, or dry pea lowered the carbon footprint of durum wheat by 28 % compared with when grown after a cereal. For a 3-year crop rotation, a pulse crop alternatively grown with an oilseed the previous 2 years lowered the carbon footprint of the 3rd-year durum wheat crop by an average 25 %. When pulse crops

were grown continuously for the first 2 years of the 3-year rotation, the carbon footprint of the 3rd-year durum crop was lowered by 34 %. These results clearly demonstrate that the integration of various crop types into a well-designed rotation substantially lowers the carbon footprint of cereal crops.

The carbon footprint of individual crop species is highly associated with crop biomass and the N concentration of various plant parts such as straw and roots. In southern Germany, it was found that farming without N fertilizers consumed less energy and generated lower emissions (Haas and Défago 2005). Similarly, in Sweden, carbon emissions decreased substantially in the production system where less fertilizer was used. Secondly, integration of agronomical practices can significantly improve the net productivity of grain crops with improved input use efficiencies. Integration of crop practices can suppress the pressure of weed competitiveness (Harker et al. 2009) and help break the life cycle of some problematic pests (Kirkegaard et al. 2008; Krupinsky et al. 2002). Also, the increased net productivity in integrated cropping systems over monoculture systems is due to the improved diversity of the microbial populations (Yang et al. 2013) and the function of microbial communities in the soil (Cruz et al. 2012). Thirdly, crop species can influence soil organic carbon dynamics (Lal 2011). Pulse-based cropping systems reduce the loss of soil organic carbon and nitrogen compared with cereal-based cropping systems (Gan et al. 2014). However, studies from the semiarid region of Canadian prairies have shown that the effect of crop species on soil organic carbon was minimal in the short term (Campbell et al. 2007). More precise assessment of the soil carbon change with cropping systems can only be achieved based on analysis of the changes in soil carbon stocks over the long term (Osborn 1996; Lemke et al. 2012).

Similarly, many other studies have also shown that the use of integrated cropping systems coupled with the

Table 2 The carbon footprint of durum wheat grown in the various 3-year cropping sequences at southwestern Saskatchewan, Canada

Years			Carbon footprint ($\text{kg CO}_2 \text{ eq kg}^{-1}$ of grain)		
1	2	3	Mean ^a	Standard error	% decrease ^b
Cereal	Cereal	Durum	0.415	0.059	0
Cereal	Oilseed	Durum	0.375	0.059	−10
Cereal	Pulse	Durum	0.330	0.052	−21
Oilseed	Cereal	Durum	0.342	0.056	−18
Oilseed	Oilseed	Durum	0.316	0.051	−24
Oilseed	Pulse	Durum	0.295	0.049	−29
Pulse	Cereal	Durum	0.328	0.053	−21
Pulse	Oilseed	Durum	0.322	0.053	−22
Pulse	Pulse	Durum	0.273	0.045	−34

^a Means of the 3 cycles of the 3-year crop sequences at each of the two locations in southwest Saskatchewan

^b Percent decrease compared with the cereal-cereal-durum monoculture system

adoption of best agronomic practices such as early seeding, optimum plant establishment, and proper crop sequencing can increase crop productivity without increasing production inputs (Kirkegaard et al. 2008; Menalled et al. 2001; Miller et al. 2003). In a UK study, the use of fungicides in combination with other improved agronomic practices, increased wheat grain yield by 1.78 t ha⁻¹ and reduced greenhouse gas emissions from 386 to 327 kg CO₂ eq tonne⁻¹ of grain or by 15 % (Berry et al. 2008). In Denmark, with optimized fertilization and improved agronomic practices, the grain yield of winter wheat increased by 8 % while greenhouse gas emissions during the production of ethanol were reduced by 1.7 g CO₂ eq MJ⁻¹ (Elsgaard et al. 2013). In Poland, fertilizers from low-carbon emitting manufacturers that were used in wheat production significantly increased the sequestration of soil organic carbon and reduced carbon emissions by 50 % (Syp et al. 2012). In New South Wales, Australia, wheat had a carbon footprint value of 0.20 kg CO₂ eq kg⁻¹ of grain for a production level of 3.5 t ha⁻¹, whereas the footprint value was reduced to 0.15 kg CO₂ eq kg⁻¹ of grain when the production level was increased to 5.0 t ha⁻¹ or a 25 % reduction of the carbon emissions with the increased yield (Brock et al. 2012).

These studies across the globe demonstrate that use of integrated agronomical practices can increase the system productivity by 15 to 59 %, reduce the carbon emissions associated with the crop inputs by 25 to 50 %, and lower the footprint of cereal crops by 25 to 34 %. Inclusion of N₂-fixing pulse crops such as chickpea, dry pea, and lentil in the rotation systems can significantly reduce the use of inorganic fertilizer and thus decrease greenhouse gas emissions in the production of field crops. Consequently, a system that includes pulses in the rotation has the lowest carbon footprint, regardless of the geographical locations.

11 Environmental conditions and carbon footprint

Climatic conditions have a large impact on the adaptation of crop species (Cutforth et al. 2007) and their footprints (Yang et al. 2014), and the intensity of the effect depends on various factors. An obvious phenomenon is the quantity of precipitation during a crop growing season that can affect N₂O emission intensity. For example, in the southern region of Saskatchewan, Canada, the long-term (1971–2010) average growing season (1 May–31 Oct) precipitation was 264 mm and the potential evaporation was 635 mm at the drier Swift Current site, and values were 317 and 605 mm, respectively, at the wetter Indian Head site. The water deficit was greater at Swift Current (371 mm) than at Indian Head (288 mm). In response to the water deficit, the average direct emission factors for soil N₂O emission from synthetic N application and

Table 3 Average grain yield, total emissions and the various sources of emissions (%), and the carbon footprint of barley crops grown at Indian Head and Swift Current, Saskatchewan, Canada, 2004–2007

Description	Indian head		Swift current	
Grain yield (kg ha ⁻¹)	3104 ^a		2250	
Greenhouse gas emissions (kg CO ₂ eq ha ⁻¹)	1003	%	654	%
N fertilizer manufacture	259	26	158	25
N fertilizer application	296	29	173	26
Crop residue decomposition	225	21	122	17
Pesticide supply and application	108	11	105	16
Various farming operation	115	12	96	15
Carbon footprint (kg CO ₂ eq kg ⁻¹ of grain)	0.281		0.317	

^a All numbers presented are the means of 3 years × 4 replicates at each experimental site

crop residue decomposition were found to be at 0.0044 kg N₂O–N kg⁻¹ N at Swift Current, 34 % lower than that at Indian Head.

Nitrogen, phosphorous, and pesticides are the main inputs in the production of barley crops. Weather conditions affect the direct and indirect emissions of the crop inputs (Table 3). In a barley study, the emission due to the use of N fertilizer (manufacture, transportation and application) was 331 kg CO₂ eq ha⁻¹ at Swift Current and 555 kg CO₂ eq ha⁻¹ at Indian Head. Consequently, the barley grown at the drier Swift Current location had about an 11 % greater carbon footprint than barley grown at Indian Head (0.317 vs. 0.281 kg CO₂ eq kg⁻¹ of grain, respectively). Although total emissions at Indian Head were generally greater than those at Swift Current, barley yields were greater at Indian Head. We defined that the carbon footprint of a field crop as a function of grain yield and total greenhouse gas emissions. Thus, to lower the carbon footprint of field crops, one could employ various means to (i) increase grain yield without increasing greenhouse gas emissions, (ii) decrease greenhouse gas emission without decreasing grain yield, and (iii) more ideally, increase crop yield while at the same time decreasing greenhouse gas emissions.

12 Conclusion

Sustainable agricultural systems are needed to produce high-quality and affordable food in sufficient quantity to meet the growing global population need for food, feed, and fuel, and, at the same time, farming systems must have a low impact on the environment. Having reviewed about 140 recent publications on the subject, we find that the challenge of meeting global food demand while lowering the environmental footprints can be alleviated by adopting various improved

agronomical practices. The key agronomical tactics include, but are not limited to diversification of cropping systems, improvement of N fertilizer use efficiency, adoption of intensified rotation with reduced summerfallow, enhancement of carbon conversion from atmospheric CO₂ into plant biomass and ultimately sequestered into the soil, use of reduced tillage in combination with crop residue retention; integration of key cropping practices systematically, and inclusion of N₂-fixing pulses in crop rotations. Integration of these improved farming practices together enables to reduce the use of inorganic fertilizers, increase the system productivity, and lower the carbon footprint. Farmers are increasingly aware that crop production is no longer a yield-income business, and the way the crops are produced will have significant environmental consequences. Over 60 % of the total emissions in food products in grocery stores stem from farm gate raw material. Farmers play a key role in ensuring the provision of low-emission materials to the food chain. There are huge gaps between the development of new cropping technologies and the implementation of the technologies in farming operations. With relevant agro-environmental policies in place, along with the adoption of improved agronomical tactics, increasing food production with no cost to the environment can be achieved effectively, efficiently, and economically.

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