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Research Paper

A decade of carbon flux measurements with annual and perennial crop rotations on the Canadian Prairies

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ABSTRACT

The long-term understanding of the carbon budget of cropping systems needs to consider varying meteorological conditions, site/soil conditions, crop selection, and management decisions. On the Canadian Prairies, a variety of crops are used in yearly rotation, often not repeating the same crop within a 3-year period. We measured net ecosystem production (NEP) in two cropping systems in southern Manitoba, Canada, for the 2006–2016 period. One system had continuous annual crops, whereas the other had a perennial phase for 4 years. NEP was calculated using the flux-gradient method, where the carbon dioxide gradient was measured with a tunable-diode laser analyser and the transfer coefficient was based on momentum similarity theory with inputs from sonic anemometer-thermometers. NEP varied from −100 (source) to +300 (sink) $g\,C\,m^{-2}y^{-1}$ among four adjacent 4-ha fields and 10 years, depending on annual crop (corn, faba, spring wheat, barley, rapeseed, soybean) and environmental conditions. There was no period of 3 years or greater when NEP in the continuous annual crop rotation was different from carbon neutral. Inserting a 4-year perennial phase of an alfalfa/grass mix created a statistically significant carbon sink for NEP ($P = 0.04$), but the perennial period itself was carbon neutral. Enhanced ecosystem respiration was observed following termination of the perennial crop. Harvest practices varied from no harvest (in the establishment year of the perennial crop), grain removal only, grain + straw removal, and straight cutting of green biomass for silage. Once harvest removals were included, 3 of the 4 fields were carbon neutral, but one annual field had net carbon losses for some periods. Ecosystem respiration averaged about twice as large as harvest removals. Net carbon (mean ± S.E.) over the 11-year period for the annual cropping system ($-78 \pm 51\,g\,C\,m^{-2}\,y^{-1}$) was not different from the annual-perennial system ($-48 \pm 47\,g\,C\,m^{-2}\,y^{-1}$).

1. Introduction

Potential loss of soil organic carbon from agricultural systems is a global concern because of soil degradation and increasing atmospheric carbon dioxide (CO_2) concentrations (e.g., Lal, 2004; Paustian et al., 2016). On the Canadian Prairies, the introduction of large-scale annual cropping systems caused soil carbon loss over the past century (Janzen et al., 1998; Smith et al., 2000). However, land in summer fallow (i.e., no crops planted in some years but weeds were controlled, normally by tillage) was responsible for much of this carbon loss (e.g., McGinn and Akinremi, 2001) and this practice has become less common over the past few decades. The potential for future carbon gain or loss depends on management practices (e.g., Janzen et al., 1998; Follett, 2001; West and Marland, 2003), but crop yield is often a higher priority for agricultural producers than soil carbon dynamics. This is complicated by the diversity of systems and management practices, coupled with location (e.g., soil type) and inter-annual climate variability.

There is a long history of carbon flux measurements over cropping systems, but many of the early measurements were only during the growing season (e.g., Desjardins, 1974; Baldocchi et al., 1981a,b; Anderson et al., 1984; Anderson and Verma, 1986; McGinn and King, 1990; Baldocchi, 1994; Anthoni et al., 2004). Over the last decade, researchers have been examining the longer-term carbon dynamics, which in agricultural systems usually involve a rotation of crops, typically at annual intervals in temperate climates. These crop rotations tend to be specific to various regions, which necessitates measurements over many different systems. For example, several groups have documented the dynamics of the corn-soybean rotation in the U.S. (Baker and Griffis, 2005; Hollinger et al., 2005, 2006; Hernandez-Ramirez et al., 2011; Suyker and Verma, 2012; Dold et al., 2017). Often, corn is

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Table 1
Agronomic and Climate Characteristics (detailed agronomy in Appendix A). Normal mean annual temperature is 3.0 °C and total precipitation is 521 mm for Winnipeg, Manitoba (1981–2010, Environment Canada, 2016).

Year	Crop (years with 2 crops indicate the perennial phase)	Planting date	Harvest dates	Soil Temp. 5-cm depth at planting (°C)	Mean Harvest removals ($g\,C\,m^{-2}$)	Annual precip. (mm)	Mean annual temp (°C)
2006	Corn	May 16	Oct 6	12.5	123	292[c]	4.6
2007	Faba	May 11	Aug 27	10.6	307[a]	559[c]	2.9
2008	Spring wheat	May 21	Sep 16	9.6	203[b]	727[c]	1.4
	Alfalfa/grass	May 28	–	12.8	0		
2009	Rapeseed	May 30	Sep 22	12.1	43	425	2.0
	Alfalfa/grass	–	Jul 6; Nov 19		193		
2010	Barley	May 22	Oct 7	14.9	55[a]	705	4.0
	Alfalfa/grass	–	Jul 11; Aug 27		151		
2011	Spring wheat	Jun 10	Sep 27	13.2	41	257	3.6
	Alfalfa/grass terminated Sep 22	–	Jun 29; Aug 5		229		
2012	Corn	May 3	Oct 18	7.9	260	335	4.5
2013	Soybean	May 28	Oct 9	11.8	125	305	1.2
2014	Spring Wheat	May 29	Sep 15	14.4	300[b]	365	1.2
2015	Soybean	May 13	Sep 29	5.4	143	510	4.1
2016	Soybean	May 19	Oct 3	11.2	137	591	4.6
mean	–	May 21[d]	–	12.4	158[d]	461	3.1

[a] Harvested as silage.
[b] Both grain and straw harvested separately.
[c] Data from Winnipeg Airport (Environment Canada).
[d] Mean of annual crop rotation only.

an annual sink whereas the following soybean year is a carbon source, once harvesting is included in the carbon budget. European studies have looked at rotations that usually have more than two crops in sequence, with measurements typically on the order of three to five years (Aubinet et al., 2009; Ceschia et al., 2010; Kutsch et al., 2010). In Europe, Moors et al. (2010) determined that CO_2 exchange was more determined by choice of crop than by differences in yearly weather.

On the Canadian Prairies, crop rotation choices are continuously evolving as a function of new crop and cultivar developments, pest pressure (weeds, disease, insects), management tools (e.g., equipment, pesticides) and a changing climate. Typically, most agricultural producers work with a 3- to 5-year rotation of various crops, although rotations can be much longer, and the exact sequence varies widely. In addition, a perennial crop could be part of the rotation, which could be present for 3–5 years before being terminated. Given that both crop choice (including rotation) and environment (weather, soil, management) are very diverse, we need many more long-term flux measurement records over these cropping systems to better understand the carbon dynamics of modern agricultural practices.

Previously we examined the carbon dynamics over three years at a site in southern Manitoba, Canada, where corn (*Zea mays*), faba bean (*Vicia faba minor*) and spring wheat (*Triticum aestivum*) were planted in successive years (Glenn et al., 2010, 2011). This period was followed by an initial comparison of two years of the annual cropping system (spring wheat, rapeseed (*Brassica napus*)) with a perennial system of alfalfa (*Medicago sativa*) mixed with timothy grass (*Phleum pratense*) (Maas et al., 2013). Since the establishment of this long-term site in 2005, we have continuously measured carbon fluxes over a variety of crops with the crop selection based on the needs for crop rotation in this area, coupled with the need for different crops for economic gains. Nitrous oxide fluxes have also been measured in parallel at this site (Glenn et al., 2012; Maas et al., 2013; Tenuta et al., 2016).

In the current analysis, our overall objective was to examine the carbon dynamics of this long-term (decade) cropping system grown in a high-latitude climate with a relatively short growing season. We further examined the impact of a short-term perennial crop phase insertion into the longer-term annual cropping system. This allowed us to test several specific hypotheses: 1) A cropping system with annual crops in rotation is carbon neutral, 2) Replacement of annual crops with perennial crops for part of the rotation has no effect on the carbon budget, 3) Carbon losses are dominated by harvest removals, and 4) Termination of a perennial crop increases heterotrophic respiration in subsequent years.

2. Methods

2.1. Experimental design and agronomic history

The site (49.64N, 97.16W, 235m.a.s.l) is located south of Winnipeg, Manitoba, Canada at the University of Manitoba Glenlea Research Station (National Centre for Livestock and the Environment). This is in the flat (< 2% slope) Red River Valley floodplain on glaciolacustrine clay with an extreme humid-continental climate (Köppen Dfb). The soils are gleyed humic vertisols (Canadian system) or typic humicryerts (U.S. system) of the Osborne and Red River Series (Ehrlich et al., 1953; Michalyna et al., 1975). The surface soil is 60% clay texture, bulk density of $1.2\,Mg\,m^{-3}$, pH_{H2O} of 6.2, and $32\,g$ organic $C\,kg^{-1}$. The fields have some poorly drained locations that can create spatial variations in crop establishment and growth.

The experimental fields are four adjacent, square 4-ha plots (2 × 2 layout) in a larger 30-ha field that is planted to the same crop as the experimental plots (diagrams in Glenn et al., 2010; Tenuta et al., 2016), a similar configuration used by other researchers (e.g., Wagner-Riddle et al., 2007). The two 4-ha adjacent fields on the east side were kept in a continuous rotation of annual crops (Fields 2 and 3, "annual cropping system") for the 2006–2016 calendar years, whereas the two on the west side included a perennial crop phase of alfalfa/grass mixture from 2008 to 2011 (Fields 1 and 4, "annual-perennial cropping system"). Note that in years with different crops on the east and west sides, the surrounding field was also split into 15-ha areas with a matching crop to the experimental plots to ensure footprint inclusion. Fields were managed using commonly practiced cultivation and fertilizer strategies for this area. The crops, and planting and harvest dates, are given in Table 1. Detailed agronomic activities are listed in Appendix A, giving fertilizer, tillage, and herbicide details.