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The surface-atmosphere exchange of carbon dioxide, water, and sensible heat across a dryland wheat-fallow rotation

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ABSTRACT

Summer fallow – the practice of keeping a field out of production during the growing season – is a common practice in dryland wheat (*Triticum aestivum* L.) cropping systems to conserve soil water resources. Fallow also depletes soil carbon stocks and thereby soil quality. The area of summer fallow has decreased by tens of millions of hectares since the 1970s in the northern North American Great Plains as producers have recognized that avoiding fallow usually confers both economic and soil conservation benefits. Observed summertime cooling across parts of this region has coincided with fallow reduction, suggesting that the role of fallow in atmospheric processes needs to be ascertained. We measured carbon dioxide, latent heat, and sensible heat flux across a winter wheat – spring wheat – fallow sequence in Montana, USA to determine the effects of dryland crop management on ecosystem carbon resources and energy partitioning at the surface-atmosphere interface. Winter wheat and spring wheat fields were carbon sinks ($F_c = -203 \pm 52$ g C—CO_2 m^{-2} and -107 ± 29 g C—CO_2 m^{-2}), respectively, during the April to September study period, but the fallow field was a carbon source of 135 ± 73 g C—CO_2 m^{-2}. Evapotranspiration in the wheat crops was over 100 mm greater than the 275 ± 39 mm observed in the fallow field during the study period. Modeled maximum daily atmospheric boundary layer height was on average 210 m higher and up to 900 m higher in fallow compared to the spring wheat field with more crossings of the modeled atmospheric boundary layer and lifted condensation level, suggesting that regional studies of the effects of fallow on near-surface temperature and moisture are necessary to understand the effects of fallow reduction on regional climate dynamics. Results demonstrate that fallow has a detrimental impact to soil carbon resources yet is less water intensive, with consequences for regional climate via its impacts on atmospheric boundary layer development and global climate via its carbon metabolism.

1. Introduction

Wheat (*Triticum aestivum* L.) provides more than 20% of the calories and protein for the global population (Hawkesford et al., 2013) and nearly 220 Mha of wheat was harvested globally in 2013 (FAO, 2013). Wheat therefore plays a central role in not only global food production, but also in the global exchange of water, energy, and climate-relevant trace gases like carbon dioxide between the land surface and the atmosphere (West and Marland, 2002; Buyanovsky and Wagner, 1998).

Our understanding of the interaction between wheat cropping systems and the atmosphere remains incomplete. Wheat has a very low canopy resistance to water vapor transport during its main growth period (Bonan, 2008), and models tend to accurately simulate latent heat flux (*LE*, see Table 1 for a list of abbreviations), and sensible heat flux (*H*) during these periods (Ingwersen et al., 2011). Aspects of the seasonal timing of crop development including ripening (Ingwersen et al., 2011) and management decisions like harvesting (Sus et al., 2010) on surface-atmosphere fluxes continue to challenge ecosystem models. Management practices including crop rotations have been identified as important contributors to carbon metabolism at the field scale (Béziat et al., 2009; Schmidt et al., 2012), but have largely been studied in winter wheat crops and/or mesic cropping systems to date (e.g. Billesbach et al., 2014; Moureaux et al., 2008). Surface-atmosphere exchange in rotations common to dryland cropping systems including spring wheat and chemical fallow (hereafter ‘fallow’) have been studied less-frequently to date.

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Table 1
A list of abbreviations with their definitions.

Abbreviation	Definition
α	Initial slope of the light response curve
α_{PT}	Priestley-Taylor coefficient
β	Gross ecosystem productivity at light saturation
γ	Psychrometric constant
γ^*	Virtual temperature inversion strength
Δh	Change in height of the atmospheric boundary layer
ε_{PT}	Intercept term of the Priestley-Taylor-type model
λ	Latent heat of vaporization
ρ_a	Density of air
ABL	Atmospheric boundary layer
c_p	Specific heat capacity
E_0	Activation energy
ET	Evapotranspiration
F_c	Carbon dioxide flux
G	Soil heat flux
GEP	Gross ecosystem productivity
h	Height of the atmospheric boundary layer
h_{LCL}	Height of the lifting condensation level
H	Sensible heat flux
H_v	Virtual heat flux
LE	Latent heat flux
P	Atmospheric surface pressure
r	Water vapor mixing ratio
RE	Ecosystem respiration
R_n	Net radiation
R_{10}	Ecosystem respiration at an air temperature of 10 °C
s	Slope of the vapor pressure-temperature relationship at saturation
SW_{in}	Incident shortwave radiation
T_a	Air temperature
T_{10}	Air temperature of 10 °C
T_{LCL}	Air temperature at the lifting condensation level
T_t	Reference temperature (227.13 K)
u^*	Friction velocity

Fallow is a common management practice in the dryland wheat-growing regions of the northern North American Great Plains to conserve water for subsequent crops (Lubowski et al., 2006). Fallow however also increases erosion (Wischmeier, 1959) and soil carbon loss (Cihacek and Ulmer, 1995), and fallow-small grain management strategies are not considered sustainable from the soil conservation perspective (Merrill et al., 1999). Management practices are changing. The area of fallow in the Prairie Provinces of Canada has decreased from over 15 Mha in the 1970s to under 2 Mha at the present (Fig. 1) as producers have realized that the water-savings benefit of fallow is outweighed by the economic losses of not planting (Dhuyvetter et al., 1996). The area under fallow in the United States has likewise decreased from 16 Mha to 6 Mha across the same time frame (Lubowski et al., 2006), largely in the northern Great Plains and other areas of the semiarid West (Fig. 1). Despite the decreasing trend in fallow area across the North American northern Great Plains, fallow remains common in many regions including major land resource area (MLRA) 52 in north-central Montana – the largest wheat-growing region in the state – where some 40% of agricultural lands may remain in fallow in any given year. In contrast, fallow has been reduced in northeastern Montana (MLRA 53) by hundreds of kha over the past decade (Long et al., 2014, 2013) as producers have adopted continuous cropping or alternate cropping practices (Burgess et al., 2012; Miller et al., 2003, 2002).

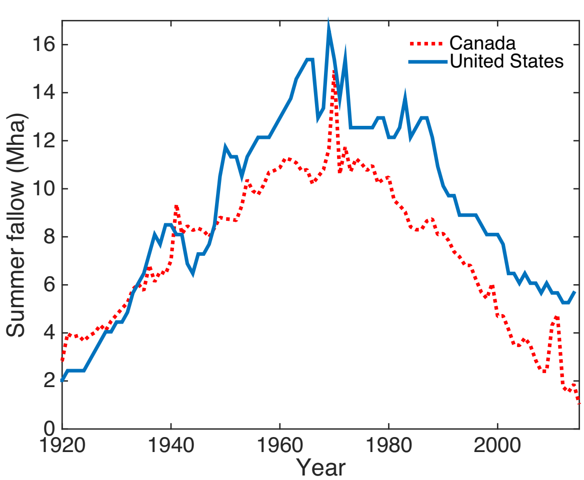

Fig. 1. Trends in summer fallow area from 1920 until the present in Canada (red dashed line) and the United States (blue solid line) using data from Statistics Canada and the United States Department of Agriculture Economic Research Service. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The widespread decline of fallow in agricultural areas of the Canadian Prairie Provinces (Fig. 1) has coincided with a summertime cooling trend since the 1970s (Betts et al., 2013a, 2013b; Gameda et al., 2007; Mahmood et al., 2014). Extreme temperature events now occur less frequently than in the recent past, maximum summer temperatures have decreased by *ca.* 2 °C, relative humidity has increased by some 7% (Betts et al., 2013b), and summer precipitation has increased by an average of 10 mm/decade across parts of the Canadian Prairie Provinces (Gameda et al., 2007). A remarkable 6 W m^{-2} summer cooling has been observed (Betts et al., 2013a); for reference, anthropogenic greenhouse gasses are responsible for a *ca.* 2.5 W m^{-2} warming globally since the dawn of the Industrial Era (IPCC, 2007). These climate benefits have only occurred during the growing season; fall, winter, and early spring temperatures have followed global trends (Betts et al., 2013b).

Studies suggest that these climate changes are the result of land management, specifically the trend away from leaving fields fallow