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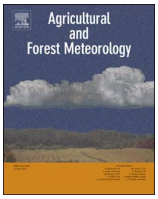

Research Paper

The challenge of reconciling bottom-up agricultural methane emissions inventories with top-down measurements

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ABSTRACT

Agriculture is estimated to produce more than 40% of anthropogenic methane (CH_4) emissions, contributing to global climate change. Bottom-up, IPCC based methodologies are typically used to estimate the agriculture sector's contribution, but these estimates are rarely verified beyond the farm gate, due to the challenge of separating interspersed sources. We present flux measurements of CH_4, using eddy covariance (EC), relaxed eddy accumulation (REA) and wavelet covariance obtained using an aircraft-based measurement platform and compare these top-down estimates with bottom-up footprint adjusted inventory estimates of CH_4 emissions for an agricultural region in eastern Ontario, Canada. Top-down CH_4 fluxes agree well (mean ± 1 standard error: EC = 17 ± 4 mg $CH_4\,m^{-2}\,d^{-1}$; REA = 19 ± 3 mg $CH_4\,m^{-2}\,d^{-1}$, wavelet covariance = 16 ± 3 mg $CH_4\,m^{-2}\,d^{-1}$), and are not statistically different, but significantly exceed bottom-up inventory estimates of CH_4 emissions based on animal husbandry (8 ± 1 mg $CH_4\,m^{-2}\,d^{-1}$). The discrepancy between top-down and bottom-up estimates was found to be related to both increasing fractional area of wetlands in the flux footprint, and increasing surface temperature. For the case when the wetland area in the flux footprint was less than 10% fractional coverage, the top-down and bottom-up estimates were within the measurement error. This result provides the first independent verification of agricultural methane emissions inventories at the regional scale. Wavelet analysis, which provides spatially resolved fluxes, was used to attempt to separate CH_4 emissions from managed and unmanaged CH_4 sources. Opportunities to minimize the challenges of verifying agricultural CH_4 emissions inventories using aircraft flux measuring systems are discussed.

1. Introduction

Methane (CH_4) is the second most important greenhouse gas (GHG) after carbon dioxide (CO_2), and contributes about 20% of the global radiative forcing due to GHGs (Kirschke et al., 2013). Its atmospheric concentration has increased by more than 150% since 1750. There are many sources of CH_4 in the terrestrial biosphere. Global CH_4 sources, which include unmanaged and managed sources, have been estimated at 678 Tg $CH_4\,yr^{-1}$ with a range of 542–852 for the 2000–2009 decade. Wetlands are the main unmanaged source and they account for 217 Tg $CH_4\,yr^{-1}$ of global CH_4 emissions (IPCC, 2013). Managed sources originate primarily from fossil fuels (96 Tg $CH_4\,yr^{-1}$), ruminants (89 Tg $CH_4\,yr^{-1}$), landfill/waste (75 Tg $CH_4\,yr^{-1}$), rice (36 Tg $CH_4\,yr^{-1}$) and biomass burning (35 Tg $CH_4\,yr^{-1}$) (IPCC, 2013). There are very large uncertainties in these estimates. In Canada, emissions from wetlands range from 16 to 29 Tg $CH_4\,yr^{-1}$ depending on the study (Thompson et al., 2017). Agriculture accounts for about 1.4 Tg $CH_4\,yr^{-1}$, approximately 88% are from enteric fermentation and the remaining 12% are from manure management systems (Environment Canada, 2015b; Karimi-Zindashty et al., 2012). Little is known about the magnitude of the CH_4 emissions from wetlands within the agricultural landscape.

Canada employs an Intergovernmental Panel on Climate Change (IPCC, 2006) Tier II methodology to estimate agricultural CH_4 emissions, which in its simplest form is the product of emission factors (EFs) and activity data (*e.g.* animal population). Country specific emission

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factors are typically obtained by either confining a small number of animals in a chamber (Beauchemin and McGinn, 2005; Beauchemin and McGinn, 2006), or in instrumented barns (Kinsman et al., 1995; Sauer et al., 1998) or by inferring CH_4 emissions through atmospheric measurements (Flesch et al., 2013) from cattle on pasture (Felber et al., 2015), in pens (McGinn et al., 2009), in feedlots (van Haarlem et al., 2008) or in barns (Gao et al., 2010; VanderZaag et al., 2014).

Several methods have been used to obtain and evaluate CH_4 emission estimates. Denmead et al. (2000) used mass-balance flux gradient measurements of CH_4 to verify IPCC inventory estimates of CH_4 emissions from an extensive grazing area in New South Wales. Judd et al. (1999) obtained comparable estimates of CH_4 emissions from a flock of sheep using half hourly averages from a flux gradient technique and measurements from individual sheep based on a sulphur-hexafluoride tracer technique. Diurnal variations of CH_4 and CO mixing ratios were used by Hsu et al. (2010) to estimate CH_4 emissions using well-documented CO emissions. With this relationship a top-down CH_4 emissions inventory was calculated for Los Angeles County which was then compared with bottom-up CH_4 emissions inventory based on IPCC methodologies.

Obtaining accurate CH_4 emission estimates for different sources in a region is challenging. There have been a number of inverse modelling studies focusing on Europe (Bergamaschi et al., 2010; Cressot et al., 2014; Manning et al., 2011) and on the United States (Kort et al., 2008; Miller et al., 2013; Zhao et al., 2009). Large discrepancies were found in both the spatial distributions and flux estimates amongst these studies (Miller et al., 2013; Vogel et al., 2012). This is primarily related to the differences in the modelling approaches (*e.g.*, different atmospheric transport models, optimization methods, *etc*.). Inversion modelling is also not capable of distinguishing interspersed sources from different sectors. Overlapping grid level sources from different sectors are typically grouped and treated as a single source. Atmospheric observations from greenhouse gas monitoring satellites such as GOSAT (Turner et al., 2015) and TROPOMI (Veefkind et al., 2012) are not likely to be useful to separate the contributions of managed and unmanaged CH_4 sources because of their coarse spatial resolution and their lack of sensitivity. Bottom-up emission estimates based on IPCC methodologies, which are used for UNFCCC reporting, poorly account for animal types, management practices and climate. Top-down CH_4 emission estimates have frequently been reported as being substantially higher than bottom-up estimates (Turner et al., 2015). This discrepancy points to the importance of being able to quantify the contribution of CH_4 sources at a wide range of scales.

Top-down measurement approaches that incorporate emissions from tens to hundreds of km^2 provide a spatial scale that can be used to verify bottom-up estimates. Aircraft flux measuring systems have previously been used to estimate the anthropogenic top-down CH_4 emissions from an agricultural area (Wratt et al., 2001); N_2O emissions from agricultural regions (Desjardins et al., 2010); CO_2 and CH_4 from a large urban center (Mays et al., 2009); CH_4 emissions from an oil and gas production region of Utah (Karion et al., 2013) and CO, CH_4 as well as a variety of halo- and hydrocarbons from the northeastern United States (Miller et al., 2012).

In this study, we examine the performance and limits of top-down, aircraft-based Eddy Covariance (EC), Relaxed Eddy Accumulation (REA) and wavelet covariance techniques to quantify CH_4 emissions from an agricultural region. We quantify the magnitude of all the CH_4 emissions in an attempt to separate the contribution of the various CH_4 sources and better understand the dynamics of these sources. We focus on the CH_4 emissions from livestock in an attempt to verify IPCC Tier II bottom-up agricultural CH_4 emissions inventory estimates using top-down estimates based on aircraft-based CH_4 flux measurements.

2. Methods

2.1. Measurements and study area

The study area is the combined Districts of Glengarry-Prescott-Russell, and Stormont-Dundas-South Glengarry located in eastern Ontario, Canada (area ≈ 7000 km^2), where agriculture occupies 62% of the land area (Ontario Ministry of Natural Resources, 2008). The remaining land consists of wetlands, mixed forest, open water and built-up areas. Agricultural activities are dominated by dairy farming, with a smaller number of beef cattle, swine, poultry, other animals and cash crops farms. Within the study area, seven 20-km transects were flown on seven days in the spring of 2011, between April 8 and May 12, generally between 1200 and 1600 EST (Table 1). The EC and wavelet covariance measurements of two days had to be discarded due to problems associated with data acquisition system of the fast response CH_4 sensor, leaving 5 days with valid flight data for comparing flux results. For each flight, one or two transects approximately perpendicular to the mean wind direction were flown using the National Research Council Canada, Twin Otter atmospheric research aircraft (Desjardins et al., 1982, 2000). Each transect was flown either three or four times at an altitude ranging from 170 to 270 m above ground level (agl) and each pass along a given transect is a run. About 50 runs were analyzed.

2.2. Flux measurements using the EC technique

High-frequency aircraft flux measurements of CH_4 and H_2O were obtained using a fast response (10 Hz) closed-path cavity ring-down spectrometer analyzer (CRDS; G2301-f $CO_2/CH_4/H_2O$ Picarro, Santa

Table 1

Overview of the aircraft measurements, U = wind speed, *dir* = wind direction, T = air temperature, T_s = surface temperature, u_* = friction velocity, σ_w = standard deviation of the vertical wind, z_i = boundary layer height, R = Incident solar radiation. Values represent the average of 3 or 4 runs per transect.

Flt.#	mm/dd	Start − End (EST)	Transect[a]	U ($m\ s^{-1}$)	*dir* (°)	T (°C)	T_s (°C)	u_* ($m\ s^{-1}$)	σ_w ($m\ s^{-1}$)	z_i (m)	R (Wm^{-2})
1	04/08	1438–1545	E_{189}	1.8	223	8.9	16.3	0.6	1.3	1600	595
			F_{189}	2.8	243	9.1	15.2	0.7	1.4		561
2	04/15	1515–1631	F_{176}	2.6	64	2.0	9.0	0.5	1.5	1300	587
3	04/19	1142–1242	$G2_{169}$	3.0	345	2.7	11.2	0.7	1.4	1300	881
4	04/27	1356–1459	D_{161}	6.9	95	21.4	25.5	0.5	0.9	1700	707
5	04/30	1339–1435	A_{163}	2.8	313	13.9	25.8	0.5	1.2	1200	933
			C_{163}	1.7	345	14.6	24.5	0.6	1.2		894
8	05/10	1243–1347	I_{159}	5.9	57	14.1	–[b]	0.6	1.4	1300	989
			I_{201}	5.8	55	13.8	–[b]	0.9	1.4		987
			I_{259}	6.0	58	13.2	–[b]	0.7	1.5		993
10	05/12	1259–1409	F_{148}	8.6	84	16.7	25.9	0.8	1.4	900	949
			F_{204}	8.7	82	16.2	25.6	0.7	1.4		966
			F_{273}	8.0	87	15.6	25.4	0.7	1.6		967

[a] Subscript following Transect gives average flight altitude in m agl.

[b] Radiative surface temperature instrument failure.