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Net ecosystem exchange of CO_2 and carbon balance for eight temperate organic soils under agricultural management

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ABSTRACT

This study presents the first annual estimates of net ecosystem exchange (NEE) of CO_2 and net ecosystem carbon balances (NECB) of contrasting Danish agricultural peatlands. Studies were done at eight sites representing permanent grasslands (PG) and rotational (RT) arable soils cropped to barley, potato or forage grasses in three geo-regional settings. Using an advanced flux-chamber technique, NEE was derived from modelling of ecosystem respiration (ER) and gross primary production (GPP) with temperature and photosynthetically active radiation as driving variables. At PG ($n = 3$) and RT ($n = 5$) sites, NEE (mean ± standard error, SE) was 5.1 ± 0.9 and 8.6 ± 2.0 Mg C ha^{-1} yr^{-1}, respectively, but with the overall lowest value observed for potato cropping (3.5 Mg C ha^{-1} yr^{-1}). This was partly attributed to a short-duration vegetation period and drying of the soil especially in potato ridges. NECB, derived from NEE and C-removal in harvested biomass, was equivalent to 8.4 ± 1.0 and 11.5 ± 2.0 Mg C ha^{-1} for the PG and RT land-use types, respectively. Means were not significantly different, $P = 0.214$, and were comparable to a wider range of high-end emission factors for managed organic soils in boreal and temperate climate zones. It was stressed that evaluation of emission factors should explicitly differentiate between data representing net C balance from a soil perspective and CO_2-C balance from an atmospheric perspective. Modelling of inter-annual variability in NEE for three selected sites during a 21-year meteorological period indicated a range of 18–67% (coefficients of variation). Yet, the robustness of these estimates and their importance for the derived emission factors needs to be substantiated experimentally.

1. Introduction

Organic carbon accumulates in wet soil ecosystems as the supply of oxygen is limited by slow diffusion in water. Thereby, photosynthetically fixed carbon in plant residues may enter anoxic settings and accumulate as peat, serving as a reservoir in the global C cycling (Joosten and Clarke, 2002). Drainage and agricultural use of organic soils reverse the carbon storage process as microbial oxidation of soil organic carbon (SOC) increases due to the effects of aeration, fertilization and tillage of the soil (Maljanen et al., 2001). Previous estimates from Finland, Sweden, and the Netherlands (Kasimir-Klemedtsson et al., 1997) indicated that organic soils under agricultural management with cereals, row crops, and grasses are net emitters of CO_2, with fluxes ranging from 2.2 to 31 Mg C ha^{-1} yr^{-1}.

In Denmark, drainage of organic soils has taken place since about 1850, and recently (1998 data) it was reported that ca. 151,000 ha were under agricultural management as estimated according to the Danish soil classification, where organic soils are defined by more than 10% organic matter (>5.9% SOC) in the upper 0–20 cm (Gyldenkærne et al., 2005). Future management of these organic soils is under current national consideration as restoration of wetlands is envisaged as a means to reduce N and P discharge to streams and rivers (Hoffmann and Baattrup-Pedersen, 2007), and also as a means to reduce CO_2 emissions (Drösler, 2005; Hendriks et al., 2007).

The annual emission of CO_2 from agricultural organic soils in Denmark was evaluated by Gyldenkærne et al. (2005) using the generic Tier 2 method of the Intergovernmental Panel on Climate Change (IPCC, 2006), i.e., by summing the products of national activity data and emission factors. The CO_2 emission factors for drained organic soils were derived from a Danish subsidence study (Pedersen, 1978) and modified data from five other North European countries (Gyldenkærne et al., 2005). For areas with permanent grass and rotational crops, respectively, the emission

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factors corresponded to 4 and 8 Mg C ha^{-1} yr^{-1} on deep organic soils (Gyldenkærne et al., 2005).

To substantiate the assessment of greenhouse gas emissions from managed organic soils in Denmark, two initiatives started in 2008. One was a new survey of the distribution of organic soils, showing that the current area is in the range of 115,000 ha (M.H. Greve, personal communication). The other initiative was a field study to estimate annual net emissions of CO_2 (this study), as well as emissions of methane and nitrous oxide (Petersen et al., 2012). Based on a 1-year study period, we here present the net ecosystem exchange (NEE) of CO_2 and net ecosystem carbon balances (NECB) of eight organic soils managed as permanent grasslands or rotational agricultural fields, cropped to barley, potato or grass. Measurements of CO_2 exchange were done with a temperature-controlled transparent chamber technique in an annual monitoring programme designed to support a national up-scaling of the emission results with temperature and photosynthetically active radiation (PAR) as main driving variables (Jacobs et al., 2007). The resulting NEE and carbon balances for the organic soils are discussed with reference to previous results from boreal and temperate climate zones.

1.1. Terms and definitions of NEE

The scientific literature is somewhat ambiguous in the terms and definitions used for carbon fluxes and balances (e.g., Randerson et al., 2002; Lovett et al., 2006). However, following Chapin et al. (2006), the NEE of CO_2 accounts for the imbalance between gross primary production (GPP) and ecosystem respiration (ER), but also encompasses inorganic sinks and sources of CO_2 (such as weathering and atmosphere–water equilibrations). In terrestrial ecosystems the latter terms are often minor (or ignored), so NEE becomes numerically equivalent to the net ecosystem production (NEP), defined as NEP = GPP − ER (Lambers et al., 1998; Kuzyakov, 2006; Chapin et al., 2009).

Notoriously, the concept of NEE uses two different sign conventions: the atmospheric sign convention defines a positive NEE as a net flux of CO_2 to the atmosphere (i.e., $|ER| > |GPP|$), whereas the ecological sign convention defines a positive NEE as a net uptake of CO_2 by the plant–soil ecosystem (i.e., $|GPP| > |ER|$). Furthermore, the two conventions use the individual signs for GPP and ER inconsistently. This means that in the literature, the rationale of NEE appears as NEE = ER + GPP, NEE = ER − GPP or NEE = −ER + GPP (e.g., Burrows et al., 2005; Syed et al., 2006; Gilmanov et al., 2007; Wohlfahrt et al., 2008). This divergence is mainly disciplinarily rooted, but may at some point call for the definition of conventions of choice.

In the present study, the atmospheric sign convention was adopted and the NEE of CO_2 was represented as NEE = ER − GPP, with ER and GPP both defined as positive values. Consequently, a positive NEE signifies a net emission of CO_2 from the plant–soil ecosystem to the atmosphere.

2. Materials and methods

2.1. Selection and characteristics of monitoring sites

Flux measurements were done from August 2008 to September 2009 at eight sites representing three major geo-regions in Denmark (Jacobsen, 1976) that also cover typical national variation in temperature, precipitation, and solar insolation (Table 1). The geo-regions were located on the Jutland peninsula and covered the sandy glacial outwash plains in the West (region *W*), the younger moraine areas in the East (region *E*), and the raised seabed landscape in the North (region *N*).

Table 1
Location, management, climate and soil characteristics for the eight study sites. Climate data represent the monitoring period (2008–2009). Groundwater and soil data are adapted from Petersen et al. (2012), with soil data shown for the two depth intervals 0–30 cm and 34–64 cm (values separated by slash). Groundwater table (GWT) in geo-region *E* was rather constant (c) during the year, whereas more variability (v) was found in geo-region *W* and *N*.

Site	Position	Geo-region	Management	Main crop	Mean annual air temperature (°C)	Total annual precipitation (mm)	Total annual PAR (kE m^{-2})	Mean annual GWT (cm)	Mean peat depth (cm)	0–30/34–64 cm peat depth		
										Organic C (%)	C:N ratio	pH (KCl)
W-AR	55°56′N, 8°26′E	*W*	AR	Barley	9.3	913	7.5	48 (v)	220	20/39	17/18	5.0/3.9
W-PG	55°56′N, 8°26′E	*W*	PG	Grass	9.6	913	7.4	42 (v)	123	16/41	18/22	4.9/3.8
E-AR	56°23′N, 10°24′E	*E*	AR	Barley/grass	9.2	579	5.8	111 (c)	72	33/41	29/29	4.9/4.3
E-PG	56°23′N, 10°24′E	*E*	PG	Grass	9.0	579	6.6	40 (c)	87	30/46	25/28	4.7/4.8
E-RG	56°23′N, 10°24′E	*E*	RG	Grass/barley	9.2	579	6.7	43 (c)	78	30/38	26/28	5.8/5.5
N-AR	57°14′N, 09°51′E	*N*	AR	Potato	8.7	702	7.2	70 (v)	77	47/31	30/25	4.5/4.2
N-PG	57°14′N, 09°50′E	*N*	PG	Grass	8.6	702	6.7	61 (v)	102	43/53	28/53	5.1/4.6
N-RG	57°14′N, 09°51′E	*N*	RG	Grass	9.1	702	7.5	70 (v)	86	45/40	28/27	4.9/4.5