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The full carbon balance of a rewetted cropland fen and a conservation-managed fen

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ABSTRACT

On a global scale, the release of greenhouse gases (GHG) from peatland drainage and cultivation are believed to account for ~5% of estimated anthropogenic GHG emissions. Drainage generally leads to peat subsidence and extensive soil loss, resulting in a diminishing store of soil carbon (C). This is a challenge for maintaining drainage-based agriculture, as such practices will eventually lead to the loss of organic soils that arable cultivation depends on. The conversion of croplands on peat to semi-natural grasslands, alongside raising water tables, is one possible way to reduce the loss of these valuable C stores. Here, we report the net ecosystem carbon balances (NECB) of two lowland peatlands in East Anglia, south-east UK. One site is a relic conservation-managed fen on deep peat, subject to active hydrological management to maintain water levels, and dominated by *Cladium* and *Phragmites* sedge and reed beds, whilst the other is a former cropland that has been converted to seasonally-inundated grazed grassland. Despite occasionally experiencing severe water table drawdown, the conservation-managed fen was a strong C sink of -104 g C m^{-2} yr^{-1}. In contrast, the grassland was a C source of 133 g C m^{-2} yr^{-1}, with gaseous carbon dioxide (CO_2) emissions being the main loss pathway, due to low water tables exposing the soil profile in summer. At each site, ditch emissions of CO_2 were moderately large (22 and 37 g C m^{-2} yr^{-1}), whilst ditch methane (CH_4) emissions (0.2 and 1.8 g C m^{-2} yr^{-1}) made a negligible contribution to the NECB, but are important when considering the ecosystem GHG balance in terms of CO_2 equivalents. Excluding dissolved inorganic carbon (DIC), fluvial C losses were 6 g C m^{-2} yr^{-1} for the conservation-managed fen and 12 g C m^{-2} yr^{-1} for the former cropland, and were dominated by dissolved organic carbon (DOC). The small fluvial C loss is the result of both sites being hydrologically isolated from the surrounding agricultural landscapes. Although the partially re-wetted cropland was still acting as a net C source, our estimates suggest that seasonal rewetting has reduced net annual C losses to ~20% of their former cropland values. Maintaining high water tables year round would potentially further reduce C losses, and shallow inundation might allow the return of wetland species such as *Phragmites* and *Typha*, perhaps as floating rafts.

"The height of a man in the life of a man." – Old East Anglian saying describing peat losses due to subsidence.

1. Introduction

Globally, approximately 300,000 km^2 (~7%) of peatlands are used for agriculture (International Peat Society, 2008), including extensive areas of lowland peat that have been drained and converted to intensive

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arable use, and are now important areas for food production (Joosten and Clarke, 2002). Drainage generally disrupts the natural functioning of the peatland carbon (C) store, leading to increased emissions of nitrous oxide (N_2O) (Haddaway et al., 2014) and carbon dioxide (CO_2), as extensive peat losses occur due to this oxidation (Hooijer et al., 2012). The most recent report of the Intergovernmental Panel on Climate Change (IPCC) emphasises the importance of CO_2 emissions from oxidation of cultivated peatlands (primarily in Europe and Southeast Asia) (Smith et al., 2014), and it has been estimated that greenhouse gas (GHG) emissions from drained and burned peatlands account for 5% of anthropogenic emissions (Global Peatlands Initiative, 2017).

As concern for peatland C stocks has grown, there has been an increased emphasis on restoring and rewetting bogs and fens that have been disturbed by human activities (e.g. Wilson et al., 2016), and the potential global importance of such work on GHG emissions was recognised in the development of a reporting methodology for wetland drainage and rewetting in the IPCC Wetland Supplement (IPCC, 2014). The Paris Climate Agreement commits nations to limiting climatic warming to less than 2 °C (Rogelj et al., 2016). This commitment will require zero net CO_2 emissions by 2050 (Matthews and Caldeira, 2008) which, because all realistic future scenarios involve some level of continued fossil fuel emission, will necessitate the development of compensating measures which remove CO_2 from the atmosphere; i.e. negative emissions. The recent "4 per 1000" initiative proposes that a significant fraction of this target could be achieved through enhanced sequestration of C into soils (Minasny et al., 2017). Wetlands, in particular, have been highlighted as being key in delivering "natural climate solutions" due to their potential to accumulate and retain C (Griscom et al., 2017). For lowland agricultural fens, it has been shown that restoration can reduce oxidation-induced losses of peat and, in some cases, lead to the re-establishment of their function as a C sink (Knox et al., 2014).

However, it can be difficult to restore agricultural land back to a properly functioning fen ecosystem (Stroh et al., 2013). Reasons for such difficulty include extensive peat loss through oxidation and the compaction of remaining peat, loss of local seed banks, heavily modified drainage systems and previous addition of silt to the peatland via warping (the agricultural practice of diverting mineral-rich river water onto peat soils to deposit sediment) (Smart et al., 1986). Where 'complete' restoration is impossible, it may nevertheless be feasible to convert agricultural land to semi-natural fen meadows, which will still bring associated increases in biodiversity and ecosystem services (Klimkowska et al., 2010), and may also reduce rates of C loss (Hendriks et al., 2007). In much of Europe, including parts of UK and the Netherlands, the target ecosystem for fen restoration is a semi-natural environment involving ongoing water-level and vegetation management (Klötzli and Grootjans, 2001), for example to maintain or enhance plant species richness (Menichino et al., 2016). However, sometimes it may be that constraints in water availability result in unexpected vegetation shifts, often in undesired directions, which may limit the success of restoration attempts (Klötzli and Grootjans, 2001).

Knowledge gaps still remain on the effects of agricultural fen restoration on C and nutrient cycling, and on how the functioning of these restored ecosystems compares to conservation-managed fens that have never been under agricultural production. For instance, Tiemeyer et al. (2016) found that CO_2 emissions increased with deeper water tables in drained peat grasslands, but could not model CO_2 fluxes across multiple sites solely as a function of water table, and suggested that additional factors such as drought stress could result in lower emissions (because CO_2 fluxes from respiration are limited by both very dry and very wet soil conditions). Contrary to this, it has sometimes been shown that drained grasslands can be CO_2 sinks, and could act as C stores depending on management practices; e.g. large amounts of biomass removal could counteract a terrestrial CO_2 sink and result in a C source (Renou-Wilson et al., 2014). However, methane (CH_4) can still be emitted by drained soils (Hendriks et al., 2007; Henneberg et al., 2015), with implications for C and GHG budgets.

The East Anglian fens are the largest and most intensively modified area of lowland peat in the UK. In their original form they occupied approximately 150,000 ha (Burton and Hodgson, 1987), but drainage and agricultural conversion has resulted in just 12,600 ha of deep peat remaining, which now stores an estimated 41 Tg of C (Holman, 2009). Of this remaining peat, approximately 800 ha exists as undrained fen, in four separate nature reserves. The aphorism quoted above, assuming a man of 170 cm living for sixty years, would result in a peat loss of 2.8 cm per year. This figure falls within the range of 0.27–3.09 cm per year (mean = 1.37 cm) for the region reported by Richardson and Smith (1977). As a consequence of peat subsidence, much of the land in the region is now below mean sea level, and a complex series of ditches, embankments, sluices and pumps control the area's hydrology. Although the region is of national significance for the production of arable and horticultural crops, several projects are now underway to return areas of agricultural land to wetland.

To understand how fen management affects hydrology and C cycling, we established an intensive field measurement programme spanning three growing seasons at two adjacent sites; one a conservation-managed fen on deep peat, and one a former cropland on shallow peat that has been converted to seasonally-inundated grazed meadow grassland. The conservation-managed fen is an example of the target ecosystem for successful rewetting in the region, whilst the former cropland represents an ecosystem that has been removed from agricultural production and set on a restoration trajectory towards a semi-natural status. Two different projects (the Wicken Fen Vision and the Great Fen Project) within the region currently aim to restore a combined total of 9000 ha of wetlands, primarily by taking agricultural land out of production (Peh et al., 2014). In addition to C sequestration, these projects aim to deliver ecosystem services such as flood protection, nature-based recreation, grazing provision and increased biodiversity (Peh et al., 2014). We therefore measured both gaseous C exchanges and fluvial C losses, thereby enabling complete C budgets to be calculated, thus determining: 1) whether the conservation-managed fen is a net C sink and; 2) what effect conversion to grassland has had on the C budget of the former arable fen.

2. Materials and methods

2.1. Field sites

Both field sites are part of the Wicken Fen National Nature Reserve which is owned and managed by the National Trust, a conservation organisation. Mean annual air temperature from an automatic weather station (AWS) on site was 9.3 °C in 2013, 10.9 °C in 2014 and 10.3 °C in 2015. Missing data from the AWS precludes the calculation of site-specific annual rainfall totals, but rainfall was 648 mm, 765 mm, and 641 mm in 2013, 2014 and 2015 at another lowland site 27 km away (Evans et al., 2016a). Rainfall was measured on the study site in 2015 using a manual rain gauge, with an annual total of 643 mm.

The conservation-managed site is referred to as the Wicken Sedge Fen (52.31 °N, 0.28 °E, area = 61 ha, 2–3 m above sea level). It lies on a surviving area of deep peat and contains large areas of reed bed that are cut on approximately a three year rotation. Sedge Fen has never been agriculturally drained, and has been under active conservation management since 1899, thereby making it the oldest nature reserve in the UK. The dominant plant species present are saw sedge *Cladium mariscus* and common reed *Phragmites australis,* with abundant reed canary grass *Phalaris arundinacea,* and some purple small-reed *Calamagrostis canescens* (Eades, 2016). A network of ditches cross the site, which are used for water level management rather than drainage; the ditches are not permanently connected to the wider river network in the region, but water may be transferred onto the fen from the adjacent river (named Wicken Lode). The fen has no defined outflow, i.e. it is not drained by a stream. Much of the perimeter is bunded to minimise