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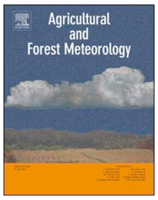

Terrestrial versus aquatic carbon fluxes in a subtropical agricultural floodplain over an annual cycle

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ABSTRACT

Aquatic carbon exports are an understudied component of catchment carbon budgets. For drained agroecosystems, the role of this aquatic pathway in offsetting the terrestrial carbon sink is unknown. Here, we present findings on the complete annual carbon budget of a subtropical agricultural floodplain in Australia. We quantified net ecosystem exchange (NEE) using eddy covariance, and aquatic carbon fluxes from drainage canals over an annual cycle, including atmospheric exchange of aquatic CO_2 and CH_4, as well as lateral exports of dissolved organic, inorganic and particulate carbon. The floodplain was a large atmospheric CO_2 sink, with an annual NEE of -900 g C m^{-2} yr^{-1} driven by the sugarcane growing season. Aquatic carbon fluxes were estimated at 24, 16, and 0.05 g C m^{-2} yr^{-1} for lateral export, CO_2 and CH_4 evasion, respectively. Between 70% and 91% of aquatic carbon was lost during flood events which occurred only 12% of the time. From these measurements and estimates of other carbon inputs and outputs from farm operations, the net ecosystem carbon budget was close to neutral at -100 (error range -289 to 215) g C m^{-2} yr^{-1}. Compared to other drained wetlands, the aquatic carbon flux was a minor component of the carbon budget.

1. Introduction

Understanding the contribution of different flux components in ecosystem carbon budgets is crucial for monitoring how carbon dynamics respond to environmental change. This can be achieved by quantifying the carbon inputs and outputs within defined boundaries and time scales. This approach represents the core concept of the net ecosystem carbon budget (NECB), for which complete accounting of all carbon flux pathways determines the net carbon accumulation or loss rate of an ecosystem (Chapin et al., 2006). Because the NECB approach includes all relevant physical, biological, and anthropogenic processes, carbon flux measurements must often be integrated across different discipline boundaries. This is especially important in ecosystems at the terrestrial-aquatic interface, where traditional land-based measurements fail to identify carbon lost via the aquatic pathway (Chapin et al., 2006; Barr et al., 2010). Fully integrated carbon budgets that account for all ecosystem processes have redefined the source/sink interpretation of some terrestrial-aquatic ecosystems (Genereux et al., 2013; Chu et al., 2015; Lundin et al., 2016).

The current role of agricultural ecosystems in the global carbon cycle is controversial. On a global scale, modelled estimates suggest that most areas of intensively managed croplands increase biomass production, yet overall agriculture has reduced total soil carbon stocks by between 8 to 13% over the last 100 years (Bondeau et al., 2007; Sanderman et al., 2017). At the finer scale, individual agricultural carbon studies spanning temperate and tropical regions show a wide range of carbon balances from net carbon sources to sinks (Kutsch et al., 2010; Bhattacharyya et al., 2014; Eichelmann et al., 2016). Many agricultural areas have been developed with extensive drainage networks, where the effect of land use and hydrological modification has altered the load and composition of carbon exported within streams and rivers (Royer and David, 2005; Raymond et al., 2008; Kaushal et al., 2014). Aquatic fluxes are often quantified in waters draining catchments with mixed land use, or are rarely inclusive of all aquatic carbon

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species (Royer and David, 2005; Raymond et al., 2008; Smith et al., 2010). Indeed, the aquatic pathway in the form of lateral export has not been accounted for within global models and fine scale studies of agricultural carbon budgets (Bondeau et al., 2007).

Cultivated wetlands represent a large area of productive agricultural environments in low lying landscapes. Agriculture is the primary land use change responsible for the estimated 50% loss in global wetland area (Verhoeven and Setter, 2009). Much research has been dedicated to understanding carbon cycling in natural and regenerated wetlands, which are often ecosystem hotspots for carbon cycling both in terms of their carbon sequestration capacity and greenhouse gas feedback (Mitra et al., 2005; Neubauer et al., 2014). The transition phase from natural wetland to agricultural production can either reduce the carbon sink or switch modified wetlands to carbon sources (Armentano and Menges, 1986). In warmer climates, this loss of soil carbon via CO_2 emissions may be particularly heightened in drained wetlands as ecosystem respiration increases (Raich and Schlesinger, 1992; Knox et al., 2015). However, very little attention has been paid to the functioning of cultivated wetlands as carbon sinks or sources after initial disturbance, or the role of the aquatic pathway as a conduit for terrestrial carbon leakage in these drained landscapes.

In Australia, many drained coastal floodplains and wetlands have been cultivated for intensive sugarcane production (Arthington et al., 1997). Sugarcane is grown in sub-tropical to tropical regions with generally high annual rainfall, and is one of the highest yielding crops in agricultural soils (De Vries et al., 2010). A limited number of studies have measured sugarcane carbon fluxes directly, yet those that have reported very high annual NEE rates of 1800 to 2685 g C m^{-2} yr^{-1} (Cabral et al., 2013; Anderson et al., 2015). It is widely accepted that sugarcane crops are very efficient at biomass carbon accumulation during their growing cycle, however isolated measurements do not provide a full assessment of farm-scale carbon budgets. Recent studies have shown that aquatic CO_2 and CH_4 fluxes from drained coastal wetlands in Australia tend to be larger than most natural aquatic environments (Gatland et al., 2014; Ruiz-Halpern et al., 2015; Jeffrey et al., 2016), and represent an unresolved flux in many agro-ecosystems. Given the preference for sugarcane in biofuel production (De Vries et al., 2010), understanding the full ecosystem carbon balance of such systems is required to achieve carbon neutral farming practices.

To advance our understanding of the carbon cycle of cultivated wetlands and the role of the aquatic pathway in carbon budgets, a complete seasonal assessment of the NECB was undertaken by integrating the aquatic carbon flux with terrestrial net ecosystem exchange (NEE). This work was carried out in a subtropical, extensively drained coastal floodplain under sugarcane production, and represents the first landscape of this type to undergo an integrated terrestrial and aquatic carbon budget assessment. The chosen site represents a well constrained “model catchment”, with distinct surface and groundwater flow paths originating within the catchment boundary (Webb et al., 2017), and a relatively controlled terrestrial carbon uptake pathway by one vegetation type (sugarcane crop).

2. Method and materials

2.1. Study site

The present study was undertaken in an agricultural wetland used for sugarcane production, situated in the sub-tropical coastal region of eastern Australia (28°17′1.69″S, 153°30′15.02″E). The site was originally a freshwater tidal wetland connected to the Tweed River estuary, which has been converted to sugarcane production for the past 40 years through drainage construction and implementation of floodgates (see Webb et al., 2016, 2017 for description of study site). The sub catchment is 1,000,000 m^2 and contains a high drainage density of 2.1 km km^{-2} and average drainage area of 3000 m^2 during baseflow conditions (Fig. 1). The site frequently experiences large rainfall events that can increase the drainage density to 12.4 km km^{-2} and the aquatic area to 1,000,000 m^2 (Webb et al., 2017). During the year of measurement (2014–2015), the region experienced above average rainfall, 1770 mm (Table S1) compared to the long term average of 1602 mm (Australian Government BOM, 2018). On average, seasonal temperatures remained consistent with historic means except with a slightly cooler winter (mean 14.6 °C, Table S1).

Sugarcane is harvested annually and is rotated to soy bean crop every 5 years. The sugarcane regrows from stems left in the ground from the previous harvest (ratoon) which are planted on mounds 20 cm above ground level. Our measurements were made in a field that was in fallow the year before and represents the first ratoon of sugarcane. The growing season commenced on 31 October 2014 (end of previous season's harvest) and ended 28 October 2015 (362 days, date of harvest), and emergence of cane shoots noted on 12 November 2014. Approximately 90 kg N ha^{-1} was applied as urea fertilizer between 1 and 14 November and ~5 kg N ha^{-1} was applied to the biomass residue immediately after the previous season's harvest. The site receives no irrigation, relying solely on rain water, and groundwater levels are artificially set to −0.5 m Australian Height Datum (AHD) below sea level. The net ecosystem carbon budget (NECB) was calculated by summing all measured carbon components and accounting for biomass inputs (i.e. the previous year's residue) and outputs (i.e. biomass harvested).

2.2. Aquatic carbon export

Measurements of carbon species including dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) were obtained biweekly throughout the year from the drain network. Additional samples were collected during a six day time series following a flood event in late January 2015, and are included in the annual study.

DOC samples were filtered through pre-combusted (450 °C for 4 h) 25 μm GF/F filters using a syringe into 40 ml borosilicate VOC vials and treated with $HgCl_2$. Samples were sealed with a Teflon rubber septa and stored frozen until analysis. Leftover filters were carefully placed into sterile polycarbonate cases and stored frozen until analysis. DOC was analyzed on an OI Aurora 1030 W analyzer (St-Jean, 2003; Maher and Eyre, 2011). POC filters were oven dried and acidified with 8% saturation HCl acid vapour in a chamber overnight. Samples were then oven dried and compacted into silver capsules for POC analysis on a flash elemental analyser (EA). DIC was calculated from total alkalinity (TA) samples and field pH as determined in CO2SYS (version 25) (Pierrot et al., 2009). TA samples were filtered through a disposable 0.7 μm GF/F Whatman filter into an air-tight container with no headspace. TA was determined by performing Gran titrations using a Metrohm Titrando automatic titrator. A Metrohm Electrode Plus was used for measuring pH during the titrations which was calibrated to Oakton National Bureau of Standards (NBS) of 4, 7, and 10. Pre-standardized 0.01 mol L^{-1} HCl^{-} was used as the titrant. The average uncertainty of duplicate TA measurements was 1.8% ± 3.7%. In cases were TA was undetectable due to low pH sample waters (i.e. $pH < 4$), DIC was assumed equivalent to measured CO_2 concentrations (detailed below). A calibrated handheld Hach® probe (HQ40d) and TROLL 9500 multiparameter sonde was used to determine drain water physiochemical parameters (temperature, DO%, pH, and salinity).

Lateral export of dissolved organic, particulate, and dissolved inorganic carbon were estimated using mean monthly concentrations and total monthly discharge. A total of 72, 61, and 77 samples were collected for DOC, POC, and DIC respectively over the year. Discharge measurements were made using a Starflow Ultrasonic Doppler flow meter positioned in a pipe culvert and calculated in 30 min time stamps as described in Webb et al., (2017). Total annual estimates for carbon export was calculated by summing all monthly values. Lateral exports are expressed in units of g C m^{-2} yr^{-1} scaled to the catchment area of