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A 19-year long energy budget of an upland peat bog, northern England

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SUMMARY

This study has estimated the long term evaporation record for a peat covered catchment in northern England. In this study, 19 years of daily evaporation were estimated for rain-free periods using White's methods. Net radiation was measured over the study period; soil heat flux was calculated from temperature profiles; and sensible heat flux was calculated assuming the energy budget was closed. The calculated time series was compared to available environmental information on the same time step and over the same time period. Over a 19-year period it was possible to calculate 1662 daily evaporation rates (26% of the period). The study showed that the energy flux to net primry productivity was a small, long-term sink of energy but this sink was a virtue of high carbon accumulation in peat catchments: in catchments where there is no long-term dry matter accumulation, net primary productivity must be a small net source of energy. The study showed that evaporation increased over the study period whilst sensible heat flux significantly declined, reflecting an increased use of sensible heat energy to meet evaporative demand. The relatively small change in evaporative flux compared to other energy fluxes suggests that this system is a "near-equilibrium" system and not a "far-from-equilibrium" system.

1. Introduction

Peatlands have received considerable interest in recent decades because they represent a considerable store of carbon and an important sink of greenhouse gas at the global scale. Gorham (1991) has estimated that 20–30% of the global terrestrial carbon resides in peatlands, which represents only 3% of the global land area. The northern peatland carbon store is estimated to be approximately 455 Gtonnes C and over the Holocene northern peatlands have accumulated carbon at an average rate of 960 Mtonnes C/yr. Under a warming climate, this vital carbon store could potentially be converted from a net sink to a net source of atmospheric carbon – a net sink of carbon in peatlands can be a net source of some carbon species and already have an adverse impact upon greenhouse gas warming potential. With increasing temperature, rates of organic matter degradation increase, leading to increased release of CO_2 through soil respiration (e.g. McKenzie et al., 1998) Increasing drought (frequency and severity) leads to activation of new enzymic processes (Freeman et al., 2001); and increased atmospheric CO_2 could itself lead to increased carbon loss (e.g. Freeman et al., 2004). These climatic effects could be enhanced by other factors including changes in atmospheric deposition of S and N (e.g. Silvola et al., 2003) or land management (e.g. Clay et al., 2009). Indeed, inter-annual comparisons of net ecosystem exchange (NEE) have shown that during dry years a peatland can change from a net sink of carbon to a net source (Griffs et al., 2000; Alm et al., 1999). Equally, land management in peatlands has often meant draining of the peat with subsequent lowering of the average water table depth (Holden et al., 2011). The majority of carbon flux pathways to and from a peat soil can be related to the position of the water table. The greater the depth to the water table, the greater the oxidation of the peat profile which has been suggested to lead to: increased flux of dissolved CO_2 (Jones and Mulholland, 1998); increased soil CO_2 respiration (Glenn et al., 1993; Funk et al., 1994 and Bubier et al., 2003); and potentially increased losses of DOC (Mitchell and McDonald, 1995). Conversely, the shallower the water table, the lower is the ingress of oxidation; the greater extent of anaerobic decomposition of the peat leading to increased CH_4 production and decreased oxidation of the CH_4 being produced (Roulet et al., 1993; Levy et al., 2012).

Complete carbon budgets of peatlands are now common (e.g. Worrall et al., 2003; Billett et al., 2004; Roulet et al., 2007; Nilsson et al., 2008) and a number of studies have begun to explore the impact of climate change and other external drivers upon the

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carbon budget, e.g. Clay et al. (2010). If carbon is being stored by peat accumulation, then peatlands are also stores of other important elements, e.g. nitrogen (N). While studies of C budgets are common, studies of N budgets are rarer even though N_2O is a more powerful greenhouse gas (Hemond, 1983; Drever et al., 2010; Worrall et al., 2012) and only a few studies have considered fluvial budgets for a range of elements (Adamson et al., 2001). Understanding the impact of climate and land-use change on the water balance of a peatland is key to understanding the future potential of these ecosystems as a carbon store or ongoing greenhouse gas store sink. Over a given period, the water balance of a peatland is a balance of precipitation input and outputs of runoff pathways (surface and groundwater) and evaporation. Under climate change, it is expected that air temperatures will increase which could limit the potential for an ecosystem to dissipate its incident energy via sensible heat flux in favour of soil heat flux and evaporation. Several studies have measured evaporation from peatlands. For example, Campbell and Williamson (1997) measured Bowen ratios over a six month period at a 20 min frequency and found Bowen ratios between 2 and 5, i.e. dominated by sensible heat flux. Similarly, for another New Zealand peat bog, Thompson et al. (1999) also found Bowen ratios that suggested dominance of sensible heat flux over evaporative flux. Conversely, Admiral et al. (2006) measured Bowen ratios over an Ontario bog and found values were typically below 1 for the snow-free season, similar to a Swedish Sphagnum mire (Kellner, 2001). It is clear, therefore, there is a range of behaviour within the diversity of peat bogs, this has contributed to diversity of methods for calculating evaporation from peatlands (Drexler et al., 2004) and attempts to understand the variation across space (Rouse et al., 2000). However, observations have always been restricted to only a few years which makes the assessment of long term changes in water and energy balances difficult.

A number of authors have extended the energy budget argument to consider the thermodynamics of ecosystems. Brunsell et al. (2011) have shown that the simplest way for an ecosystem to shed a change in incident energy is to increase evaporation as this is the most efficient means of diffusing entropy for a system that is thermodynamically "far-from-equilibrium" (Ozawa et al., 2003). However, this analysis and hypothesis has not been tested as long term energy balance data were not available. Alternatively, Addiscott (2010) has demonstrated that for a "near-equilibrium" system water loss would be minimised and changes in the amount of incident energy would be dissipated through sensible heat flux. Neither Brunsell et al. (2011) nor Addiscott (2010) had actually energy or water budget data upon which to test their model results. A simple test of the differences between these two system states would be to measure the sensitivity of evaporation to a change: if the change is absorbed by increasing evaporation then a system trying to maximise its entropy loss and is in a "far-from-equilibrium" state whereas if evaporation decreases in response to change then it is acting to minimise loss and is "near-equilibrium".

Therefore, the purpose of this study is to estimate change in the long-term energy budget of a peat ecosystem as a test of how the environment may adapt to long term change.

2. Approach and methodology

The energy budget of an ecosystem can be considered as:

$$R_n = H + G + \lambda E + P + e \quad \text{(i)}$$

where R_n = net radiation (W m^{-2}); H = sensible heat flux (W m^{-2}); G = soil heat flux (W m^{-2}); λE = latent, or evaporative, heat flux (W m^{-2}) where λ is the heat of vapourisation (2260 kJ kg^{-1}); P = primary production (W m^{-2}); and e = residual error. The residual error term is included as there are other terms that cannot be estimated as they are often so small and these are assumed to be negligible in comparison, indeed P is often not included even when ecosystem energy budgets are considered (Kellner, 2001). The approach of this study was to estimate the components of Eq. (i) for a single study over as long a period of years as possible.

2.1. Study site

Moor House and Upper Teesdale National Nature Reserve (NNR) is situated in the North Pennine upland region of the UK (Fig. 1). The Moor House NNR is a terrestrial and freshwater site within the UK Environmental Change Network (ECN). The ECN collects various hydrological and water quality data from the Trout Beck catchment that lies within the Moor House NNR. The Trout Beck catchment occurs mainly above 450 m O.D. with the highest point being the summit of Cross Fell at 893 m O.D (National Grid Reference NY 756326, N54°41′18″ W2°22′45″). The underlying geology is a succession of Carboniferous limestones, sands and shales with intrusions of the doleritic Whin Sill (Johnson and Dunham, 1963). The solid geology is covered by glacial till and colluvial material whose poor drainage qualities facilitated the development of blanket peat during the Holocene. Blanket peat covers 90% of Trout Beck catchment (Evans et al., 1999). The vegetation of the reserve is dominated by *Eriophorum sp.* (cotton grass), *Calluna vulgaris* (heather) and *Sphagnum sp.* (moss). The mean annual temperature (1931–2006) was 5.31 °C. Air frosts were recorded on average on 99 days in a year (1991–2006, Holden and Rose, 2011). Mean annual precipitation (1953–1980, 1991–2006) was 2012 mm (Holden and Rose, 2011). An automatic weather station is situated within the catchment (Fig. 1) with hourly recording of rainfall by tipping bucket raingauge; the recording of air and soil temperature at 0, 10 and 30 cm below the soil surface; and solar radiation. In addition, a network of five piezometers has been monitored hourly for the depth to the water table, and manual calibrated weekly, since October 1994. Discharge has been measured from the catchment outlet on an hourly time scale since 1991. Note that there was only one automatic weather station in the catchment and only one network of piezometers. This monitoring was sited so as to be representative of the catchment but inevitably there will be heterogeneity and this has been considered in this catchment by Joyce et al. (2001). However, the approach of this study is to consider the energy budget at the monitored site and catchment data is only used to check water balances.

For reasons of the methodology used at study, i.e. it is not possible to estimate on days with snow cover, no term for the latent heat of fusion was included in Eq. (i) was not considered in the study.

2.2. Net radiation (R_n)

The automatic weather station installed on the site has included the monitoring of net radiation (Kipp solarimeter – error of 1% at 1 W m^{-2}) since 1992, but to complement the period of record of other data sets, the net radiation was summed on a daily basis from January 1995.

2.3. Evaporation (λE)

Evaporation was estimated using the method of White (1932), where the daily evaporation (E in mm) is estimated from change in water table depth:

$$E = S_y\left(d_1 + 24\frac{(d_5 - d_1)}{4}\right) \quad \text{(ii)}$$

$$S_y = Ae^{B(d_{max} - d_1)} \quad \text{(iii)}$$