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Upland grasslands in Northern England were atmospheric carbon sinks regardless of management regimes

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ABSTRACT

Continuous exchange of carbon (C) in the forms of carbon dioxide (CO_2) and methane (CH_4) occurs between the atmosphere and the terrestrial ecosystem. These greenhouse gases (GHGs) contribute significantly to global warming when present in the atmosphere. Thus, there is growing interest in understanding better ways of managing terrestrial ecosystems so as to increase or fully utilize their capacity to sequester GHGs, or reduce emissions, and mitigate climate change. In this study, we examined the fluxes of CO_2 and CH_4 in two upland grassland locations (Nidderdale and Ribblesdale) in northern England with contrasting lithologies and under: 1) traditional hay meadow and 2) conventional pasture management. Net ecosystem exchange (NEE) and ecosystem respiration (ER) were measured for 12 months from June 2016 to May 2017, alongside other environmental variables such as soil temperature and moisture, and photosynthetically active radiation (PAR). Results showed that the grasslands were a net atmospheric C sink, with an uptake of 1822–2758 g CO_2-eq m^{-2} $year^{-1}$. This C uptake is greater than those reported in other European grasslands due to low ER. The Ribblesdale hay meadow had the lowest C uptake (1822 g CO_2-eq m^{-2} $year^{-1}$) likely due to low available soil nitrogen (N) resulting from the absence of N fertilization. This has implication for agri-environment schemes that discourage the use of inorganic N fertilizers. Warmer condition in Ribblesdale was implicated as the cause of higher C efflux relative to Nidderdale, which has implications for future climate change. The CH_4 fluxes were very low (-0.36 to -0.44 g CH_4 m^{-2} $year^{-1}$) and did not differ significantly between management regimes. It is recommended that future research should prioritise the overall GHG balance of upland grasslands and their inter-annual and decadal variability.

1. Introduction

Removing and storing atmospheric carbon (C) by the terrestrial ecosystem is a key strategy that has been recognised widely for mitigating climate change. The terrestrial ecosystem takes up atmospheric carbon dioxide (CO_2) via photosynthesis and releases it back into the atmosphere through respiration. Atmospheric methane (CH_4) is also taken up by aerobic soils (Lowe, 2006) and released into the atmosphere under anaerobic conditions (Van den Pol-van Dasselaar et al., 1999). The net balance between these processes of C uptake and C release determines an ecosystem's potential contribution to climate change. Net ecosystem exchange (NEE), the difference between CO_2 uptake via photosynthesis (gross primary productivity, GPP) and CO_2 released by respiration (ecosystem respiration, ER), is an important measure of C flux that has been used to assess the C sink-source status of terrestrial ecosystems (Chen et al., 2013; Kang et al., 2013; Moinet et al., 2016). Net CH_4 flux (expressed as CO_2 equivalent – CO_2-eq) can be added to NEE to give a better understanding of C sink-source status and global warming potential (GWP).

The NEE of grasslands varies greatly, with both negative (C sink) and positive (C source) values reported in different parts of the globe (Novick et al., 2004). In Europe, for example, annual NEE of grasslands ranges from a net source of $+627$ g CO_2 m^{-2} to a net sink of -2394 g CO_2 m^{-2} (Supplementary Table 1). Although annual and decadal variability in grasslands' NEE occurs, under similar management and environmental conditions, this variability is usually small (Jacobs et al., 2007; Peichl et al., 2011). The large variability in NEE between grasslands has therefore been attributed to the effects of management activities and environmental characteristics such as precipitation, soil type, soil temperature and moisture (Jacobs et al., 2007; Polley et al., 2008). However, the direction of reported management effects on C flux is not consistent because grasslands subjected to specific management activities such as grazing (Haferkamp and MacNeil, 2004; Kjelgaard et al., 2008; Owensby et al., 2006; Skinner, 2008) and fertilization (Bardgett and Wardle, 2003; Fang et al., 2012; Harpole et al., 2007; Welker et al., 2004; Xia et al., 2009) still have both negative and

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positive NEE values. Under similar environmental conditions and management duration, differences in management effects are most likely due to management intensity which differs across grasslands and influences a range of ecosystem processes that determine the net C flux. For example, grazing intensity and livestock stocking density influence the net C flux in grasslands (Klumpp et al., 2007) through effects on aboveground biomass offtake, residue accumulation, manure distribution, soil compaction and aeration, and soil temperature and moisture, all of which create optimal or unfavourable conditions for plant growth and soil microbial activities (Chiavegato et al., 2015). The rate of fertilizer application to grasslands similarly influences net C flux by stimulating plant growth and microbial decomposition (Ammann et al., 2007; Schmitt et al., 2010; Skiba et al., 2013; Zeeman et al., 2010).

Determining the exact effect of management activities on C flux is further complicated because managing grasslands often involves a combination of activities such as inorganic fertilizer application, manure addition, cutting of vegetation for hay or silage and/or direct grazing by livestock (e.g. Supplementary Table 1). Additionally, these management activities interact with environmental factors. For example, nitrogen (N) addition stimulates plant productivity e.g. increase in gross ecosystem photosynthesis (Xia et al., 2009), leaf area index and shoot/root ratio (Cheng et al., 2009) but this is only effective when there is ample supply of water to the ecosystem (Harpole et al., 2007). The C sequestration potential of grasslands is also influenced by the nature of their underlying soils and the material from which the soils were formed (soil parent material). Managed grasslands with mineral soils tend to sequester more C than managed grasslands on organic soils (Jacobs et al., 2007). This happens because mineral soils offer physical protection to organic C (OC) via encapsulation within aggregates and adsorption by clay minerals (Jones and Donnelly, 2004). Physical protection of OC is lacking in organic soils, rendering them more susceptible to microbial decomposition of organic matter (OM) and C release, depending on soil moisture conditions. Soil parent material is considered an important factor in C flux because it influences soil physical and chemical properties (Shrestha et al., 2014). For example, acid-forming parent materials such as siliceous stones and alkaline-forming parent materials such as limestones exert significant control on the pH of their resulting soils (Mijangos et al., 2010), and soil pH correlates positively with soil CO_2 efflux (Chen et al., 2016). Soil parent material also exerts a strong influence on soil texture and mineralogy (Araujo et al., 2017), which determine the surface area of soil particles available for OC occlusion as well as soil moisture retention and availability to both plants and soil microbes.

Despite the complex interactions between management and environmental conditions, there is an emerging pattern of C flux in managed grasslands. Net uptake of atmospheric C (i.e. negative NEE values) has been reported mostly in managed grasslands underlain by mineral soils (Jacobs et al., 2007) and where soil moisture was not limiting for plant growth (Hao et al., 2013; Rigge et al., 2013). On the other hand, net C efflux (i.e. positive NEE) in managed grasslands has been associated with organic soils (Gilmanov et al., 2007), seasonal increase in soil temperature (Cui et al., 2014; Frank et al., 2002; Jones et al., 2006), an increase in soil pH (Chen et al., 2016), and when soil moisture available for plant growth is reduced during periods of high evapotranspiration and low precipitation (Novick et al., 2004; Wang et al., 2016). However, it is not yet clear how different management regimes affect C flux in grasslands that are characterized by mineral or organo-mineral soils formed from different parent materials but under similar environmental conditions such as temperature and moisture.

Over time, and under constant management and environmental conditions, the C sequestration potential of grasslands will reach an equilibrium level or saturation point (Six et al., 2002; Smith, 2014). However, until the saturation point for a grassland is attained, appropriate management practices are needed to ensure that the C sequestration potential is fully achieved. Even after saturation, management practices that prevent the loss of accumulated C will still be necessary. There is still significant potential to increase C sequestration in temperate grasslands (Jones and Donnelly, 2004) and poorly managed grasslands can be improved to increase its C sink capacity and also protect its C stock from loss (Smith, 2014). By identifying and adopting management practices that enhance C sequestration, grasslands will contribute significantly in climate change mitigation (Rogiers et al., 2005). Intensively managed grasslands reportedly had a greater C uptake (NEE = -848 g CO_2 m^{-2} $year^{-1}$) compared to extensively managed grasslands (NEE = -239 g CO_2 m^{-2} $year^{-1}$) during 1997–2006 period in some parts of Asia, Europe and North America (Gilmanov et al., 2010). This was most likely because the intensively managed grasslands were more productive with an average GPP of 5767 g CO_2 m^{-2} $year^{-1}$ than the extensively managed grasslands (GPP = 2708 g CO_2 m^{-2} $year^{-1}$) (Gilmanov et al., 2010). Increased productivity in intensively managed grasslands is often as result of fertilizer application (Yue et al., 2016). However, fertilizer application is discouraged in some grasslands due to environmental concerns which include protecting biodiversity and improving the quality of water courses. For example, agri-environmental schemes in the UK typically are targeted towards these environmental benefits but the consequences for ecosystem C flux have not been extensively explored.

Within the UK, upland grasslands are considered sensitive environments because they are unsuitable for crop production but have important conservation values as they contain species of plants that are scarce in Europe, and are breeding grounds for nationally scarce birds and amphibians (English Nature, 2001). These areas mainly occur at 250 – 300 m above sea level and are predominantly managed for livestock production (Stevens et al., 2008) under both intensive management regimes, including fertilizer application to improve forage productivity, and extensive management regimes. The latter are prescribed by environmental stewardship schemes which aim to enhance biodiversity and usually entail planting of wild flowers, cutting for hay or silage only at specific times of the year, and no inorganic fertilizer applications.

Most C flux studies of the managed UK upland grasslands have so far been carried out in Scotland (e.g. Gilmanov et al., 2007; Jones et al., 2017; Quin et al., 2015), and all reported negative NEE, indicating their C sequestration potential (Supplementary Table 1). Methane flux was measured in only one study, which reported a negligible contribution to the net ecosystem C flux (Jones et al., 2017). It is difficult to draw conclusions about the effect of management intensity on C flux in these upland grasslands, however, because of differences in soil type between extensively and intensively managed sites. NEE was lower on extensively managed grassland on organic soils (-161 g CO_2 m^{-2} $year^{-1}$; Quin et al., 2015) compared to intensively managed grassland (grazed, fertilised and cut for silage) on mineral soils (NEE = -218 to -1324 g CO_2 m^{-2} $year^{-1}$; Gilmanov et al., 2007; Jones et al., 2017). In order to guide new agri-environment schemes designed to deliver multiple benefits, there is a need to isolate the effects of management from inherent environmental characteristics.

In this study, our aim was to examine the ecosystem CO_2 and CH_4 fluxes in upland grasslands in northern England: 1) at two locations underlain by different parent materials, and 2) under traditional hay meadow and conventional pasture (cut for silage or permanently grazed) management regimes. We hypothesize that: 1) all the grasslands will be a net C sink, with the grasslands under traditional hay meadow management gaining more C than the grasslands under conventional pasture, 2) grasslands of siliceous stone-derived soils will gain more C than the grasslands of soils formed from limestone, and 3) the flux of C in all the grasslands will be significantly influenced by microclimate.