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Soil carbon cycling and storage along a chronosequence of re-seeded grasslands: Do soil carbon stocks increase with grassland age?

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ABSTRACT

Agricultural grasslands comprise over 50% of the total land area of the UK and provide important ecosystem services that include livestock and forage production. These services are rarely measured against the effects that key management practices might have on the long-term ability of grassland soils to cycle and store carbon (C). The common management practice of re-seeding (i.e. the ploughing and seeding of grasslands with more productive grass cultivars) can cause significant soil disturbance; yet the net long-term effects of re-seeding on soil C gains and losses in permanent grasslands are poorly understood. Here, we selected a chronosequence of 45 permanent grasslands across Northern Ireland with a well-documented history of single re-seeding events over the last 50 years. Second, we asked whether and how soil C cycling and storage might differ between recently re-seeded 'young' grasslands and increasingly 'older' (or never re-seeded) grasslands. We measured (1) soil CO_2 fluxes, (2) soil C stocks, (3) the C content of different soil aggregate fractions, and (4) root C stocks. We found that soil CO_2 fluxes were significantly higher in recently re-seeded, 'young', grasslands. However, total soil C stocks (0–20 cm depth) did not increase in 'older' grasslands despite these grasslands showing greater root C stocks. Instead, soil C stocks significantly decreased with increases in soil bulk density. Higher soil bulk density was also associated with lower C content in smaller organo-mineral aggregate sizes (i.e. more recalcitrant C pools) regardless of grassland age (time since re-seeding). Overall, our results suggest that management-induced effects on key soil physical properties, i.e. bulk density, may have significantly greater implications for C sequestration in permanent grassland soils than high disturbance, but infrequent, re-seeding events.

1. Introduction

Agricultural grasslands are a defining feature of the rural landscape in the United Kingdom, constituting over 50% of all agricultural land (Perkins et al., 2000). These grasslands are of major agronomic importance, being used primarily for the production of livestock and forage (Smit et al., 2008; Power, 2010). Grassland soils are estimated to contain at least 20% of all terrestrial soil carbon (C) and have the potential to store higher amounts of C than arable soils (Conant et al., 2001; Acharya et al., 2012; Gützloe et al., 2014). Some studies have suggested that a significant proportion of grassland C stocks are stored in plant below-ground biomass (Jackson et al., 2002; Adair et al., 2009). Grassland C stock capacity is not only dependent on inherent ecosystem and climate characteristics (Johnston et al., 2009; Manning et al., 2015), but also on the frequency and intensity of common agricultural management practices (Ellert et al., 2001; Soussana et al., 2004; Soussana and Lemaire, 2014).

The majority of UK grassland management activities aim to optimise agronomic productivity, thereby increasing economic returns. Consequently, these grasslands are subject to applications of organic and inorganic fertilisers, applications of (usually calcic) lime, livestock grazing, and older swards are often re-seeded with newer cultivars of *Lolium perenne* L. (perennial ryegrass) and/or *Trifolium* spp. (clover). Fertiliser and liming additions and livestock grazing are associated with changes in nutrient availability and cycling, changes in microbial activity and, to a greater or lesser degree, soil physical disturbance (Smith, 2008; Bagchi and Ritchie, 2010; Power, 2010; Marklein and Houlton, 2012). In particular, the process of re-seeding old grassland swards by the traditional mould-board plough method is intrinsically coupled with high levels of soil disturbance, and has been linked to changes in soil

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nutrient cycling (Bhogal et al., 2000; Al-Kaisi et al., 2005), soil disaggregation and increased organic matter mineralisation leading to reduced soil C stocks (Krull et al., 2003; Lal et al., 2004; Soussana et al., 2004; Smith, 2014). Previous studies have also demonstrated that physical disruption of grassland soils by tillage prior to re-seeding can cause increased soil CO_2 emissions (Aslam et al., 2000; Risch and Frank, 2006; Willems et al., 2011). However, many of these investigations focussed on the effects of agricultural management on below-ground C stocks within intensively managed grassland systems where high frequencies of re-seeding are responsible for soil disturbance. There is still a paucity of information with regard to how soil disturbance might affect soil C storage and cycling in permanent grasslands that have been recently re-seeded and grasslands that have not been ploughed for many years.

In this study we selected a chronosequence of Irish grasslands based on time since their last re-seeding event and measured (a) soil CO_2 fluxes during the growing season (b) soil C stocks (c) the C content of different aggregate soil fractions, and (d) root C stocks. Our study included 45 permanent grasslands which are distributed across 3 different soil types in Northern Ireland, UK, and which have comprehensive management history records dating back at least 50 years.

Our study set out to test the following hypotheses: (1) based on previous findings (Aslam et al., 2000; Willems et al., 2011) we expect that soil CO_2 effluxes measured over the main growing season will be higher in recently re-seeded grasslands as opposed to grasslands that have not been re-seeded for increasingly longer time periods; (2) we predict that re-seeding will result in lower soil and root C stocks in more recently re-seeded grasslands, and (3) we expect that re-seeding will determine changes in aggregate soil size fractions following soil disturbance.

2. Materials and methods

2.1. Site description

Grasslands were selected at two lowland farm sites in County Antrim (A1; 54°45′N, 5°55′W; A2; 54°41′N, 6°12′W) and one lowland farm site in County Fermanagh (F; 54°22′N, 7°43′W), Northern Ireland (Fig. 1). All farms are located at similar elevations above sea level (90–150 m). The regional climate is temperate and relatively humid; with an annual average air temperature and mean annual precipitation of 10 °C and 800–900 mm at sites A1 and A2 and 8.5 °C and 1300 mm at site F respectively (Sweeney, 1997)

Soils at the Antrim sites are moderately drained brown earths and clay–loam underlain by Tertiary basalt till while the Fermanagh site is a poorly drained surface water gley underlain by Carboniferous limestone, shale and till (Cruickshank, 1997). Soil pH (0–20 cm depth) is 5.7, 6.1 and 6.3 at sites A1, A2 and F respectively. All grasslands are dominated by *L. perenne* L. (perennial ryegrass). Historically, farming activities within these grasslands have focused on livestock production (dairy and/or beef); grasslands are therefore typically grazed on a rotational basis by cattle or cut for silage three times a year. All grasslands are fertilised with both organic and inorganic fertilisers. The three farm sites were selected for study on account of their detailed management histories, which date back a minimum of 20 years. Within each farm site, three individual grassland replicates were chosen within five specific age categories indicative of time since the last re-seeding event i.e. (i) $\leq$2 years; (ii) 3–6 years; (iii) 7–11 years; (iv) 12–16 years and (v) $\geq$17 years (some of the older grasslands within these farms have not been re-seeded for 100 years or more). All grassland replicates chosen for study had been re-seeded once only with *L. perenne* L. and *Trifolium* spp. (*Trifolium repens* L. or *Trifolium pratense* L.) seed mixes. Re-seeding of selected grasslands was by traditional mouldboard plough tillage to approximately 20 cm depth, followed by harrowing and rolling. Other management practices varied between sites and are summarised in Table 1.

2.2. Soil CO_2 flux

Monthly measurements of soil CO_2 emissions during the growing season, between 1st May and 31st August 2012, were quantified using the dynamic open chamber method in each grassland (EGM-4 analyser with SRC-1 Soil Respiration Chamber; PP Systems, Hitchin, Hertfordshire, UK). Three replicate measurements were taken at eight randomly chosen ‘spots’ in each of the 45 grasslands. Soil CO_2 flux was calculated as the difference between CO_2 in- and out-flow concentrations (Smith et al., 2008).

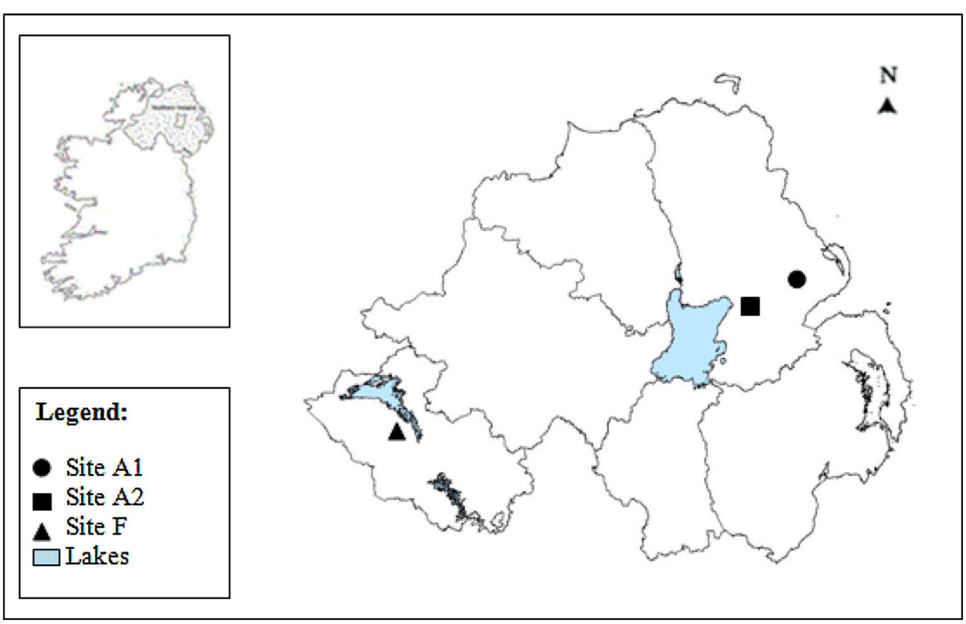

Fig. 1. Location of the three farm sites, which are distributed across Northern Ireland.