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Long-term nitrogen deposition increases heathland carbon sequestration

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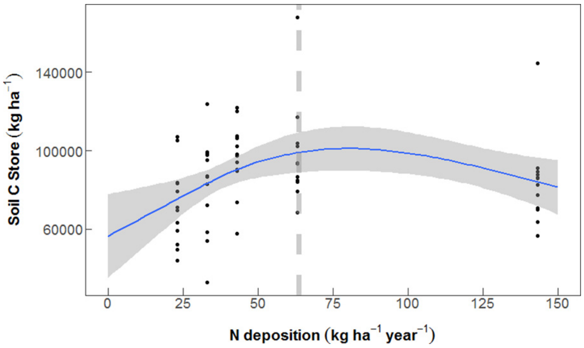
HIGHLIGHTS

- The negative impacts of nitrogen deposition could be partially mitigated through its fertilisation effect on plant growth.
- A long-term heathland N addition experiment has found large gains in plant, litter and soil carbon in response to elevated N.
- Initial estimates of landscape-scale C sequestration are high; however, as a proportion of CO_2 emissions they are small.

GRAPHICAL ABSTRACT



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ABSTRACT

The large increases in reactive nitrogen (N) deposition in developed countries since the Industrial Revolution have had a marked impact on ecosystem functioning, including declining species richness, shifts in species composition, and increased N leaching. A potential mitigation of these harmful effects is the action of N as a fertiliser, which, through increasing primary productivity (and subsequently, organic matter production), has the potential to increase ecosystem carbon (C) storage. Here we report the response of an upland heath to 10 years of experimental N addition. We find large increases in plant and soil C and N pools, with N-driven C sequestration rates in the range of 13–138 kg C kg $^{-1}$. These rates are higher than those previously found in forest and lowland heath, mainly due to higher C sequestration in the litter layer. C sequestration is highest at lower N treatments (10, 20, and 40 kg N ha^{-1} yr^{-1} above ambient), with evidence of saturation at the highest N treatment, reflecting a physiologically aged *Calluna vulgaris* (*Calluna*) canopy. To maintain these rates of sequestration, the *Calluna* canopy should be managed to maximise it's time in the building phase. Scaling our results across UK heathlands, this equates to an additional 0.77 Mt CO2e per annum extra C sequestered into plant litter and the top 15 cm of heathland soil as a result of N deposition. The bulk of this is found in the litter and organic soil horizons that hold an average of 23% and 54% of soil C, respectively. This additional C represents around 0.44% of UK annual anthropogenic GHG emissions. When considered in the context of falling biodiversity and altered species composition in heathland, policy focus should remain on reducing N emissions.

1. Introduction

Since the Industrial Revolution and throughout most of the 20th century the level of reactive nitrogen (N) in the atmosphere (primarily

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NH_3, NH_4^+, NO_x, NO_3^-, and organic N) has increased due to fossil fuel burning and agricultural intensification (Galloway et al., 2004). Between 1860 and 1990, there was a 10-fold increase in reactive N, with a further doubling predicted by 2050 (Galloway et al., 2004). This greatly enhanced atmospheric N deposition has had profound effects on ecosystem functioning, including reduced terrestrial plant species diversity, altered species composition, and leaching of N to freshwater habitats following N saturation (Stevens et al., 2004; Clark and Tilman, 2008; Dise et al., 2011; Phoenix et al., 2012; Field et al., 2014).

Potentially counteracting these negative effects of elevated N deposition is increased carbon (C) sequestration into ecosystems through enhanced plant growth (Yue et al., 2016) and, in some cases, a retardation of long-term decomposition rates (Berg and Laskowski, 2006), thereby mitigating rising atmospheric CO_2. In forests, both regional-scale N-gradient studies and N-addition experiments have demonstrated N-driven increases in ecosystem C storage ranging from 12 to 36 kg C kg N^{-1} ha^{-1} (De Vries et al., 2006; Hyvönen et al., 2007; Pregitzer et al., 2007). However, most of the additional C stored in forests in response to N deposition is in new tree biomass rather than soil (Nadelhoffer et al., 1999), with high rates of soil C turnover further suggesting that forests represent poor long-term soil C stores (Tipping et al., 2012; Mills et al., 2014). In contrast, ecosystems such as bogs and heathlands, that primarily sequester new C in soil can be significant C sinks for hundreds or thousands of years (Dise, 2009). This is due to high moisture levels and vegetation rich in recalcitrant compounds (e.g. *Sphagnum* mosses and ericaceous plants such as *Calluna*) that limit decomposition rates, causing a build-up of soil organic matter (Anderson and Hetherington, 1999; Berg and Laskowski, 2006).

Heathland ecosystems occur throughout much of the UK and north-western Europe, with closely related ecosystems in Western Australia (for example *E. impressa* heathland) and New Zealand, the oak-heathlands of eastern America, and arctic dwarf-shrub tundra. All of these habitats are characterised by vegetation in the Ericaceae family and nutrient-poor, acidic soils. As such, heathlands represent potentially important long-term soil C stores: in the UK alone, they sequester around 120 Mt C in topsoil (0–15 cm) (Ostle et al., 2009); with some soil and ecological overlap existing between bog and heathland. Overall, UK soil C storage is around 10,000 Mt (all depths) and 1600 Mt (top 15 cm) (Emmett et al., 2010), almost half of which is in the organic rich soils of bogs and heaths (Milne and Brown, 1997).

However, direct experimental evidence of changes in C accumulation in response to N deposition in heathland is limited. N has been shown to increase plant growth and litter production of the key heathland species *Calluna* (Caporn et al., 1995; Power et al., 1995) and significant increases in heathland soil and plant N pools in response to N addition have been observed (Pilkington et al., 2005a). Earlier work on smaller plots suggested that N addition enhanced soil C sequestration (at Ruabon Moor-the subject of this study), largely through the increasing dry weight of the organic soil horizon and maintenance of C/N ratios (Evans et al., 2006). This work suggested a soil C increase of between 20 and 34 kg C kg N^{-1} addition, but assumed a fixed C% for peat and mineral soil of 39.3 and 3.9 respectively, bulked soil samples, and less real-world realistic N additions of 40, 80 and 120 kg N ha^{-1} yr^{-1}. A study in a lowland heath in north-west England estimated a slightly lower sequestration rate of 20 kg C kg N^{-1} due to lower N retention in the more sandy soil (De Vries et al., 2009; Evans et al., 2006; Pilkington et al., 2005a). In south-east England, C sequestration estimates based upon N pools in soil and vegetation were approximately 33 kg C kg N^{-1} (De Vries et al., 2009). However, neither of these estimates are based on direct measurement of C, instead they use measurements or model simulations of N pools and stoichiometric relationships to convert N to C.

Here we report the first detailed analysis of organic and mineral soil C content in response to experimental N addition on an upland heath ecosystem. We also upscale the data to estimate the magnitude of N induced C sequestration at a landscape scale. We hypothesise that 1) N addition increases the rate of sequestration of C in the organic and mineral soil horizons, 2) that C/N stoichiometry is not fixed and therefore the rate of C sequestration will vary in response to N addition, and 3) N-induced sequestered C in heathland is a potentially significant sink in relation to the CO_2 equivalents ($CO_{2\ eq}$) emitted in the UK through human activities.

2. Methods

2.1. Study site

Ruabon Moor is an upland heath situated at an altitude of 480 m, approximately 6 km north of Llangollen in North Wales, UK (Fig. 1, UK Grid Reference SJ224491). Annual precipitation is approximately 1000 mm, and total inorganic N deposition in 2008 was estimated as 23.1 kg N ha^{-1} yr^{-1} from APIS (Air Pollution Information System) data, which uses the CBED model (APIS, 2008). The canopy is dominated by *Calluna*, although where burning has taken place or a gap in the canopy occurs naturally, *Vaccinium myrtillus* grows well before it is shaded out by *Calluna* regrowth. Understory vegetation consists mainly of the moss *Hypnum jutlandicum*; this combination of vegetation gives the site a British NVC classification of H12 *Calluna* – *Vaccinium myrtillus* heath (Rodwell, 1991) or a European EUNIS classification of F4.2. Soil is an iron pan stagnopodzol (F.A.O. Placic Podzol) (Evans et al., 2006). N additions (of 0, 40, 80 and 120 kg N ha^{-1} yr^{-1}) to 20 plots at the site began in 1989 (Caporn et al., 1995) and these 'old' plots (1 × 1 m) were used by de Vries et al. (2009) in their study of N-induced C sequestration. In 1998, 36 rectangular (2 × 2 m) 'new' plots were established. N as NH_4NO_3 solution is mixed with rainwater collected at the site and

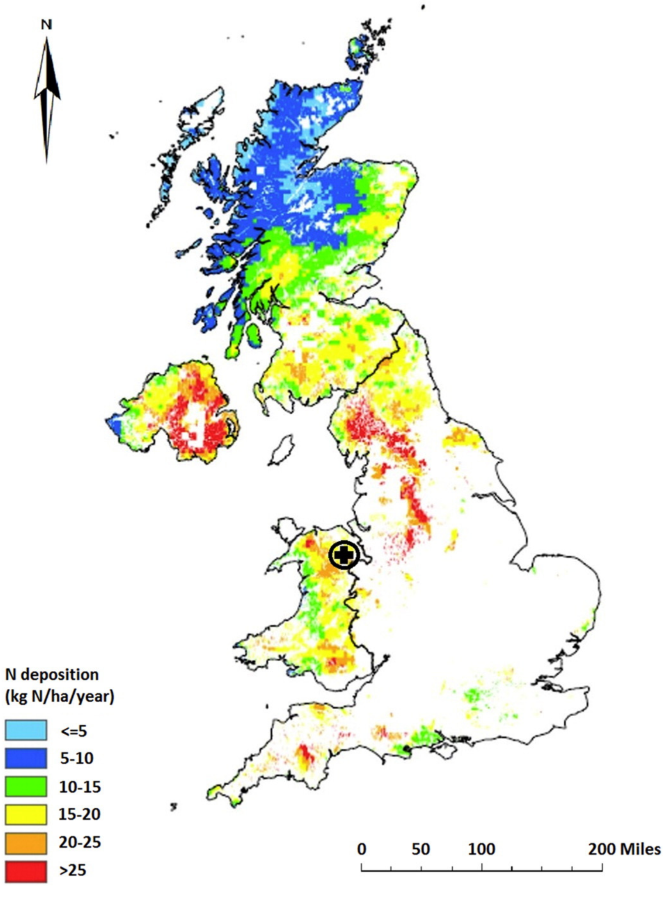

Fig. 1. The study site on Ruabon Moor in North Wales (marked with a ⊕) over a UK dwarf shrub heath distribution map shaded by nitrogen (N) deposition. UK heathland N deposition range is 2.7 to 63.6 kg N ha^{-1} yr^{-1}.