Agriculture, Ecosystems and Environment 185 (2014) 133–143

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Restoration of upland heath from a graminoid- to a *Calluna vulgaris*-dominated community provides a carbon benefit

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ARTICLE INFO

Article history:
Received 21 May 2013
Received in revised form
17 December 2013
Accepted 22 December 2013
Available online 20 January 2014

Keywords:
Molinia caerulea
Nardus stricta
Moorland
Uplands
Carbon sequestration
Restoration
pH

ABSTRACT

Restoration of degraded upland habitats has the potential to improve carbon (C) sequestration, thus helping offset national greenhouse gas emissions. Here we test the hypotheses (1) that degraded upland heath, dominated by graminoids, will have higher rates of soil respiration and smaller C pools than long established, *Calluna vulgaris* (*Calluna*) dominated upland heath, and (2) that restoration of degraded heath will increase carbon pools and decrease soil respiration towards that of "target" *Calluna* heath.

Soil respiration and total and recalcitrant C stocks in above- and below-ground vegetation and in the topsoil (to a depth of 15 cm) were estimated at seven upland sites in Northern England and Scotland. Three vegetation types were present at each site; graminoid-dominated upland heath that had formerly been *Calluna*-dominated upland heath ("degraded"); restored upland heath, converted from graminoid to dwarf shrub dominance ("restored") and long-established, *Calluna*-dominated ("target") upland heath.

Soil respiration did not differ between the three vegetation types. Degraded areas contained a larger C pool in the vegetation but a lower soil C pool and total C stock than target areas. Restored areas held similar vegetation, soil and total C stocks to those of target areas. All areas had similar pools of recalcitrant C in their vegetation, but both target and restored areas contained more recalcitrant C in the soil, and in total, than degraded areas.

The C benefit of restoration varied between sites, partly due to the abundance of *Molinia caerulea* in degraded vegetation at some sites, but the overall C benefit of restoring *Calluna*-dominated upland heath was 0.60 ± 0.70 t C ha^{-1} yr^{-1} since restoration. Restoration also increased the size of the recalcitrant C pool, which will increase C residence time and hence soil C accumulation in the longer term. Thus restoration of degraded areas is a valid option for promoting C sequestration within upland heath.

1. Introduction

UK soils represent a pool of 6–7 billion tonnes of carbon (C), of which a large majority resides in organic upland soils (Emmett et al., 2010; Schils et al., 2008). The UK uplands are under great pressure from many different land uses and land use changes (Holden et al., 2007; Ostle et al., 2009). It is increasingly being recognised that land management and land use change have the potential to significantly alter C cycling and provide important mitigation against increasing greenhouse gas emissions (Dawson and Smith, 2007; Guo and Gifford, 2002; Ostle et al., 2009; Post and Kwon, 2000). In order for the UK to achieve an 80% reduction in greenhouse gas emissions by 2050 (UK Climate Change Bill, 2008) more understanding of the effects of upland land use on soil C dynamics is needed. Upland dwarf shrub heath (upland heath) is a UK habitat with the potential to provide substantial C sequestration and hence contribute to national greenhouse gas emissions abatement. Upland heath soil has a high C concentration (284.9 g C kg^{-1}) and density (89.9 t C ha^{-1}) in the top 15 cm of the soil profile and has historically undergone dramatic shifts in vegetation composition (Emmett et al., 2010). Thus, restoration of this habitat could present a positive opportunity for C management.

There are a globally important 1.2 million hectares of upland heath within the UK (Carey et al., 2008). It is dominated by the evergreen dwarf shrub *Calluna vulgaris* (*Calluna*) and typically occurs on soil with a shallow organic layer (<50 cm). Due to its range of plant and invertebrate communities and unique bird assemblage, upland heath is designated a UK Priority Habitat (Thompson et al.,

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http://dx.doi.org/10.1016/j.agee.2013.12.022

1995; UK BAP, 2008). Upland heaths are often managed by rotational burning for sporting interests (red grouse *Lagopus lagopus* shooting); they also provide grazing for domestic livestock, particularly sheep and have long been valued for aesthetic, recreational and rural economic reasons (Gimingham, 1995; Holden et al., 2007).

During the second half of the last century, through a combination of historically high stocking densities of sheep and intensive burning regimes, upland heath suffered a dramatic decline in extent (Holden et al., 2007). In recent years the area of upland heath has stabilised but the condition of the habitat remains variable (Carey et al., 2008; Williams, 2006). Areas previously dominated by *Calluna* are now in a degraded state, dominated by single graminoid species which reduce biodiversity as well as grazing quality (Gimingham, 1975) and affect other upland heath ecosystem services, such as C storage. *Calluna* is a relatively slow-growing species, with low primary productivity and respiration, and produces poor quality, recalcitrant litter which is resistant to decomposition (De Deyn et al., 2008; Grime and Hunt, 1975; Heim and Schmidt, 2006; Jalal et al., 1982). Graminoids exhibit contrasting traits (De Deyn et al., 2008) and thus a shift from evergreen shrubs to deciduous graminoid species has the potential to alter key C cycling processes (Chapin, 2003; De Deyn et al., 2008, 2009; McLaren and Turkington, 2010; Quin et al., 2013; Ward et al., 2007, 2009). This is evident from many occurrences of where woody shrub encroachment has occurred in graminoid-dominated systems, generally resulting in increased soil and vegetation C pools, although there are obviously exceptions (Barger et al., 2011; Bradley et al., 2006; Eldridge et al., 2011; Knapp et al., 2008; Montané et al., 2010). Therefore restoration of areas now dominated by graminoids, enabling vegetation community reversion towards dwarf shrub cover, could increase C stocks of upland heath in the UK.

Investigation of the impact of upland habitat restoration on vegetation recovery and associated C cycling has focused on the highly organic soils of peatland ecosystems (Artz et al., 2008a,b; Lucchese et al., 2010; Waddington and Day, 2007; Waddington et al., 2003). The restoration of *Calluna* on graminoid-dominated upland heath has not been aimed at C sequestration, but rather at restoring target species. Most studies focused on investigating which high and/or low intensity methods (e.g. graminoid specific herbicide, rotovation, grazer exclusion) have the most success (Britton et al., 2000; Mitchell et al., 2008a,b; Pakeman et al., 2003). However, a recent study by Medina-Roldán et al. (2012) investigated the impact of seven years of grazer removal on soil C stocks in upland grassland. They found the ratio of dwarf shrub to graminoid increased significantly but, despite the contrast between dwarf shrub and graminoid vegetation, which produced significant differences in litter accumulation and microbial activity, no change was detected in the soil C stock. More research is needed to investigate how restoration of graminoid-dominated areas of upland heath influences C dynamics and whether it is a viable management option for improving C gain accumulation.

This study compares graminoid-dominated upland heath ("degraded"), restored heath dominated by *Calluna* ("restored"), and long-established, *Calluna*-dominated heath ("target") at seven upland sites across the UK in terms of: (1) C stocks in the vegetation, litter and upper soil horizon; (2) the proportion of C held in recalcitrant forms; and (3) the rate of respiratory CO_2 efflux from the soil. The hypotheses are that target heath contains larger total and recalcitrant carbon pools, and has lower rates of soil CO_2 efflux, than degraded heath, and that restoration of degraded heath will increase carbon pools and decrease soil respiration towards those of target heath. Should this prove to be the case, it would provide a reason to restore upland heath additional to that of habitat restoration.

2. Materials and methods

2.1. Field sites

This study utilised a very valuable resource of existing long-term, large scale upland management projects which had been implemented by land owners over the previous 14–20 years, hence enabling us to investigate the consequences of "real world" management practices. Field work was carried out during June and July 2010 at seven upland heath restoration project sites in England and Scotland, at each of which degraded vegetation, restored areas and long-established in-tact heath occur in close proximity (Table 1, Table S1, Fig. 1). All sites were traditionally managed as grazing land. Plots had been established at each site in 2003 by Littlewood et al. (2006a); six plots in each of degraded, restored and target vegetation. Degraded areas were dominated by either *Molinia caerulea* (*Molinia*) or *Nardus stricta* (*Nardus*) (Table 1, Table S1); *Calluna* was present at very low abundance in some of the degraded areas. Restored areas were previously similar to the degraded areas but due to restoration management are now dominated by *Calluna*. Restoration was by either grazer exclusion or mechanical restoration (a combination of herbicide application, scarification and reseeding). Target areas are long established *Calluna*-dominated upland heath. All *Calluna* sampled was in the building phase of its life-cycle, between 6 and 15 years old (Gimingham, 1975). At the time of sampling all vegetation types at all sites were open to low intensity grazing (with the exception of the restored area at Ben Lawers which still had intact sheep exclosures). Soils at all sites were acidic (pH 2.9–5.0) (Littlewood, 2005) and highly organic, with differing depth of the organic layer (Table S1).

2.2. Vegetation biomass sampling and analysis

We determined the total C content and proportion of recalcitrant C in aboveground parts of *Calluna* and other species grouped by functional type, and in roots of all species combined. At each plot the total aboveground vegetation was harvested down to the top of the litter layer (the layer of detached, relatively undecomposed plant debris) within a 0.5 m × 0.5 m quadrat. Each quadrat was chosen to represent the vegetation composition of the immediate area. Where *Molinia* was dominant, forming large,

Table 1
Upland heath restoration projects surveyed.

Site	Code	Lat/long	Degraded state	Start of restoration	Restoration method
Ben Lawers	bl	4°15.6′ W, 56°30.8′ N	*Nardus stricta*	1990	Grazing control
Bowland	bo	2°34.7′ W, 53°56.7′ N	*Molinia caerulea*/*Nardus stricta*	1996/1997	Grazing control
Carlecotes	ca	1°44.6′ W, 53°31.4′ N	*Molinia caerulea*	1992	Mechanical
Derwent 1	d1	1°44.6′ W, 53°25.5′ N	*Molinia caerulea*/*Nardus stricta*	1994	Mechanical
Derwent 2	d2	1°44.6′ W, 53°26.5′ N	*Nardus stricta*	1994	Mechanical
Geltsdale	ge	2°33.7′ W, 54°54.9′ N	*Molinia caerulea*	1995	Grazing control
High Moor	hm	2°03.6 W, 53°13.1′ N	*Molinia caerulea*	1995	Mechanical