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Research article

Above-ground biomass accumulation patterns in moorlands after prescribed burning and low-intensity grazing

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ABSTRACT

Shrub-dominated ecosystems such as moorlands are recognized internationally as cultural landscapes with high biodiversity conservation value. These ecosystems are commonly managed using prescribed burning to reduce the impact of wildfires, increase biodiversity and ecosystem productivity for grazing. Given that ecosystem responses are sensitive to the above-ground balance within the vegetation, knowledge of the above-ground biomass accumulation patterns on moorlands is an important issue for planning management action. Here, we used the replicated long-term manipulative grazing and burning experiment at Moor House (UK) to explore the cumulative effects of multiple fires and low-grazing. The study comprised a comparison between no-burn reference plots (no-burn since ca. 1923) and an experiment where all plots were burned in 1954/1955. Within the experiment, the effects of low sheep grazing vs. no grazing and three burning rotations were tested (no-burn since 1954/1955, repeat-burning at 10- and 20-year intervals). We hypothesized that prescribed burning and grazing will interact, affecting both the above-ground biomass and vegetation height. The results reveal that although the main above-ground biomass was constrained in three fractions (litter, *Calluna* and bryophytes) there was no significant effect of sheep-grazing or its interaction with prescribed burning (graze × burn) on any biomass variables or vegetation height. Significant reductions in above-ground biomass and vegetation height were only produced by repeated burning. There were no significant differences in biomass or vegetation height between the no-burn since 1954/1955 treatment and reference plots. Moreover, *Calluna* biomass and vegetation height showed a positive significant asymptotic association with time since the last burn with an asymptote at 20 and 15 years after fire, respectively. This work demonstrates that burning rotations lower than 20 years reduced the above-ground biomass and vegetation height on this moorland compared to stands unburned for more than 50 years. In order to maximize the C fixation, fire return-intervals should be around the *Calluna* biomass accumulation asymptote 20 years since last fire. Furthermore, the vegetation height asymptote of 36 cm, indicating when the vegetation is at its maximum stage, could be a useful tool for guiding when to implement prescribed burning for carbon accumulation purposes.

1. Introduction

For many shrub-dominated ecosystems around the world, prescribed burning, the deliberate application of fire under specific conditions (Fernandes and Botelho, 2003), is a widely-used management tool to reduce the impact of wildfires, prevent succession to woodlands, improve wildlife habitats, or increase biodiversity and ecosystem productivity for grazing livestock (Pakeman et al., 2003; Calvo et al., 2005; Borghesio, 2009; Keeley et al., 2012; Lee et al., 2013a). As these benefits usually last for only a few years after fire, repeated prescribed burning is needed for effective management (Ascoli et al., 2009). Therefore, prescribed burning planning requires an understanding of the vegetation response to repeated burning, which involves the implementation of long-term monitoring programs (Fernandes et al., 2013). These long-term monitoring programs help to unravel the potential consequences of the use of prescribed burning on ecosystems, their recovery and their carbon balance (Ascoli et al., 2009; Velle et al., 2012), as well as to define the most effective rotation interval required under present and future global climatic change scenarios (Keeley, 2005). Unfortunately, despite the importance of having well-designed management plans, there is a lack of long-term

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empirical studies testing the effects of repeated prescribed burning on shrub-dominated ecosystems (e.g. Boer et al., 2009).

One of the main difficulties in prescribed burning practices is to quantify the patterns in above-ground carbon balances. Many complex interactions may exist between fire and other management practices where biomass is consumed, such as with grazing. It is well known that grazing is an important biomass consumer in many terrestrial ecosystems and it can interact with fire in many shrub-dominated ecosystems (Rigolot et al., 2002; Ascoli et al., 2013; Johansson and Granström, 2014). Grazing can also influence the above-ground biomass accumulation patterns after fire, which are primarily controlled by a balance between plant growth, litter production (both negatively affected by grazing; Evlagon et al., 2012) and decomposition rates (positively affected; Riggan et al., 1988). This is especially true in the early post-fire years when pasture quality is greatest (Fuhlendorf et al., 2009). As a consequence, prescribed burning might be expected to be implemented in grazed systems at longer time intervals as grazing slows down the biomass accumulation (Johansson and Granström, 2014). However, despite the great interest in prescribed burning as a management tool in shrub-dominated ecosystems, there are few studies that investigate the post-fire biomass accumulation patterns under the influence of grazing (but see Rigolot et al., 2002, Ascoli et al., 2013). Studies of the interactions between plant growth rates and management treatments such as grazing and repeated burning are essential for developing appropriate management strategies within shrub-dominated ecosystems. Indeed, repeated prescribed burning along-side grazing are the predominant tools for the management of north-west European moorlands (Harris et al., 2011a; Lee et al., 2013b; Velle et al., 2014).

In Great Britain upland moors, many of them growing on blanket bog (ombrotrophic mire) have a very high conservation value of international significance (Bain et al., 2011; Lee et al., 2013a). These moors are currently cultural landscapes that have been created and maintained by anthropogenic activity, mainly sheep grazing and prescribed burning (Rosenburgh et al., 2013). Whilst fire has been used for hundreds, perhaps thousands of years (Simmons, 2003), its use has increased in the last 200 years to enhance the productivity of the moors for sheep grazing and especially for red grouse (*Lagopus lagopus scoticus* Latham) (Harris et al., 2011a; Lee et al., 2013a). Nowadays, approximately, 65% of British upland moors are managed using prescribed burning for the benefit of red grouse (Sotherton et al., 2009). Hence, their sustainable management is important in terms of both the local economy and biodiversity (Harris et al., 2011a).

Prescribed burning will inevitably affect the vegetation carbon balance from the moorland systems as the fire moves through it. Carbon balance will depend on the biomass consumed by the fire (initial instantaneous loss) and the ecosystem resilience (Mitchell et al., 2000), i.e. the time it takes for the ecosystem to recover via plant growth and biomass accumulation during the inter-fire interval. Where prescribed burning is done carefully within the approved burning season (winter months in Great Britain; Anon, 2007), using “cool burn” or “pressurized fuel-assisted” burning (Harris et al., 2011a), these losses should be minimized as some vegetation remains after the fire and the peat should be left relatively unaffected. After burning there is often relatively rapid vegetation recovery and hence carbon accumulation during the post-fire succession, and the overall aim should be to produce a balanced budget over a specified time period. In this sense, there is still little information available in moorlands subjected to prescribed fires, being often conflicting. In a moorland area in central England, Allen et al. (2013) used a modelling approach to predict that over a 50 year period the longer the fire rotation-interval, greater the accumulation of above-ground biomass (vegetation and litter). However, Clay et al. (2010) observed, in terms of carbon budgets, that prescribed burning can reduce global C releases in comparison to long-term unburned areas; i.e., taking into account fluvial and gaseous fluxes such as dissolved organic carbon, particulate organic carbon, excess dissolved CO_2, release of CH_4, net ecosystem respiration of CO_2, and uptake of CO_2 through primary productivity. Therefore, knowledge of the above-ground biomass accumulation patterns on moorlands is fundamental for global change research, and for planning management action; therefore, further research is needed to disentangle the effect of different fire rotation-intervals in defining above-ground biomass as C sink and source. Undoubtedly, such knowledge will assist in determining the fire rotation-interval that optimizes C fixation by means of vegetation growth.

As far as moorland conservation management in Great Britain is concerned, a major issue that needs to be addressed is a quantification of the effects of low-intensity grazing, current on many moorland ecosystems, and repeated prescribed burning on the above-ground biomass during the prescribed burning/post-fire recovery cycle. To address this, we measured above-ground biomass within the replicated long-term manipulative grazing and burning experiment at Moor House National Nature Reserve (Rawes and Hobbs, 1979; Lee et al., 2013a). This experiment has a history of approximately 90 years of known low-grazing pressure and fire rotations at different intervals (10, 20 and 56/57 years). This experiment, therefore, represents a unique opportunity to quantify the cumulative effects of multiple fires and low-grazing on biomass accumulation and its related parameters such as the dry weight of component fractions (e.g. *Calluna vulgaris* (L.) Hull, litter, bryophytes, graminoids and other vascular plants) and vegetation height. For all of these measures we assessed the effect of (a) grazing (grazing vs. no grazing), (b) the different rotation intervals (short-, long-, and unburned for 50 + years) and their interaction. In addition, we modelled plant growth through time since the last burning; as both the total accumulated, and as the absolute growth rate (AGR).

Essentially, our aim is to determine what is the optimal fire return-time based on the biomass patterns found. For that, we made a comparison of biomass accumulation with literature sources and we tested two main hypotheses: First, that the shorter fire return-intervals will produce greater reductions in above-ground biomass and vegetation height. Second, it has been shown that grazing slows down the above-ground biomass accumulation by consumption, especially in early post-fire years when pasture quality is greater (Velle et al., 2012; Johansson and Granström, 2014); therefore, we expect that biomass reduction by grazing will be greater in shorter fire return-intervals.

2. Material and methods

2.1. Study area

The study site is within the Moor House National Nature Reserve (hereafter referred as Moor House, Table 1), which is located in the northern Pennines, a range of hills that form the backbone of England (54°41′34.4″N, 2°24′28.1″W). The experimental site is on the eastern side of Hard Hill, a gently-sloping, high-level plateau (600–650 m; Heal and Smith, 1978); and it is situated on blanket bog (>50 cm peat, the widely-accepted definition for blanket peat in the UK; Costigan et al., 2005). The vegetation at Moor House can be described as *C. vulgaris*–*Eriophorum vaginatum* blanket mire (M19) and *E. vaginatum* blanket and raised mire (M20) communities within the British National Vegetation Classification (NVC; Rodwell, 1991). Thus, the most common species are *C. vulgaris*, *E. vaginatum* L., *Pleurozium schreberi* (Brid.) Mitt. and *Sphagnum capillifolium* (Ehrh.) Hedw. Here, *Calluna* was the dominant species in the