Ecological Indicators 62 (2016) 76–85

Contents lists available at ScienceDirect

Ecological Indicators

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

Prescribed moorland burning meets good practice guidelines: A monitoring case study using aerial photography in the Peak District, UK

Katherine A. Allen *, Pierre Denelle, Francisco M. Sánchez Ruiz, Victor M. Santana, Rob H. Marrs

School of Environmental Sciences, University of Liverpool, Liverpool L69 3GP, UK

ARTICLE INFO

Article history:
Received 11 May 2015
Received in revised form 9 November 2015
Accepted 12 November 2015
Available online 14 December 2015

Keywords:
Remote sensing
Moorland management
Burning rotation interval
Monitoring practice
Conservation
Environmental policy

ABSTRACT

Upland moors in the UK have been managed for centuries using rotational prescribed-burning, but in recent years there has been contentious debate over its continuing use due to varying effects on moorland ecosystem services. Prescribed-burning should only be carried out using good-practice codes, which include restrictions on the size, location and frequency of burns. Good burning practice is an indicator of management standards and habitat condition in moorland landscapes. However, there has been little attempt to assess management performance with respect to these restrictions. We investigated prescribed-burning on a case-study estate (Howden Moor) in the Peak District National Park from 1988 to 2009 using management maps and aerial photography. The annual area burned (0.9%) was far below recommendations (10%) and patches were in keeping with the target sizes specified (mean ± se: 2370 ± 70 m^2). The risk of a large or escaped fire was very low, with less than 1% of fires greater than 15,000 m^2. However, only 28.9% of the total burnable area was burned, leaving the rest unmanaged and accumulating fuel. Future guidelines might recommend the application of prescribed-burning across the range of *Calluna vulgaris* growth phases, to reduce fuel load and promote biodiversity at the landscape scale. We show that vegetation mapping and aerial photography are an effective method for monitoring prescribed-burning practice on moorlands. The information derived from such monitoring studies should lead to greater confidence in the standard of prescribed-burning and adherence to good-practice guidelines and requirements imposed by statutory authorities.

1. Introduction

Moorlands are unique landscapes and provide habitat for internationally important assemblages of flora and fauna (JNCC and Defra, 2010). These semi-natural habitats are a priority for nature conservation and are protected under the UK Biodiversity Action Plan and under Annex I of the EU Habitats Directive. Three quarters of the world's remaining moorlands are in the UK and moorland covers about 25% of UK uplands (Moors for the Future, 2007). UK moorlands also store in the region of 3000 Mt carbon (SEERAD, 2007) providing a globally significant carbon sink. The condition, community composition and carbon storage capacity of moorlands can vary considerably according to management, including grazing, drainage and prescribed fire, as well as geographical and climatic constraints (Holden et al., 2007; Allen et al., 2013). Understanding what management is appropriate and how it should be applied is, therefore, crucial for protecting and improving the condition of moorlands globally, and preserving the ecosystem services they provide.

Rotational prescribed-burning has been used for centuries to manage upland moors in the UK and is also practiced on moors and heaths in northern Europe (e.g. Måren et al., 2010; Velle et al., 2012) where the vegetation is usually dominated by *Calluna vulgaris* (L) Hull (hereafter '*Calluna*'). Traditionally, burning provided grazing for sheep (*Ovis aries* L.) but, since the 1800s, burning has been used increasingly for red grouse, *Lagopus lagopus scoticus* (Latham), production for sporting interests. The aim of prescribed-burning is to remove old, leggy growth of *Calluna*, and to encourage the development of new, succulent shoots, as well as reducing vegetation height (Gimingham, 1972). *Calluna* is a fire-adapted species that re-sprouts rapidly from burned stem bases, as well as showing increased regeneration from seed after fire (Måren et al., 2010)

* Corresponding author.
E-mail address: kaallen@liverpool.ac.uk (K.A. Allen).

http://dx.doi.org/10.1016/j.ecolind.2015.11.030
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provided temperatures and exposure times do not exceed lethal values (e.g. Velle et al., 2012). The area of land where prescribed-burning is used has been estimated at between 6600 and 17,000 km^2 in upland Britain (Bunce and Barr, 1988; Grant et al., 2012; Hudson, 1992) and a recent assessment using satellite imagery suggested burning occurred in 8551 1-km squares across Scotland, England and Wales; although the latter study did not fully separate prescribed-burning from wildfire (Douglas et al., 2015).

Recently there has been considerable contentious debate over the continuing use of prescribed-burning in moorland management (Tucker, 2003; Bain et al., 2011) due to conflicting requirements by different stakeholders (*Marrs* et al., 2007; Pakeman et al., 2011). Moorlands provide a range of ecosystem services (M.E.A., 2005) including provisioning (agricultural, potable water supplies), regulatory (carbon sequestration) and cultural (recreational and sporting) services; as well as being important ecosystems for conservation (Bain et al., 2011). Burning of any kind will inevitably release above-ground carbon to the atmosphere through combustion, but may also transform some to a more recalcitrant form, i.e. charcoal. It may also affect water quality and purification costs by increasing the amount of dissolved organic carbon in runoff (Yallop and Clutterbuck, 2009), although the evidence for this remains unclear (Holden et al., 2012).

In addition, as these ecosystems are dominated by a fire-adapted shrub (*Calluna*), there is the potential for wildfire, i.e. fires started either accidentally (lightning, hot particles from power lines, escaped management fires, disposable barbeques, road-traffic accidents, aircraft crash) or through arson. Where wildfire occurs, there will be reduction or loss of some ecosystem services for a variable time-period, depending on the extent of the area affected and both the intensity and severity of the fire (Keeley, 2009). Wildfires tend to occur in spring or summer (Legg et al., 2007) when vegetation is dry. They may cover large areas and burn with high intensity and severity, sometimes consuming all the above-ground fuel load and significant amounts of underlying peat (Maltby et al., 1990). Conversely, prescribed-burning aims to achieve 'light' fire severity (Keeley, 2009), whereby surface litter, mosses and shrubs are charred or consumed, but the soil organic layer remains largely intact (Davies et al., 2010). There is some evidence from models based on European forests that prescribed-burning could reduce the area of wildfires (Narayan et al., 2007; Vilén and Fernandes, 2011), through reduced fuel load and creation of fire breaks. However, Bradstock et al. (2012) suggested negligible benefits of prescribed-burning on wildfire control in temperate Eucalypt forests. It is possible that prescribed-burns in UK moorlands create fire-breaks to impede wildfire spread (Costigan et al., 2005), but there is little information on the role of prescribed fire in wildfire mitigation in this system (Albertson et al., 2010).

Prescribed-burning in the UK should be carried out using good-practice burning codes (Anon, 2007, 2011) to minimise negative impacts. Burning is restricted to winter months (October–mid April), and many managers are required to have their burning plans scrutinised by a statutory agency. The aim of these practices is to (a) reduce any impact on ground-nesting birds, (b) leave some areas unburned (Anon, 2011), (c) ensure burn sizes are relatively small, and (d) ensure that burning practice conforms to agreed rotation lengths. Adherence to these criteria provides an indicator of the condition of the habitat and the standard of management it is subject to. Well managed land should comprise of a mosaic of patches with varying ages of *Calluna*, which allows plant species diversity to be maximised (Harris et al., 2011a, 2011b). Without such management, a virtual monoculture of *Calluna* forms, leading to lower diversity and increased fuel load. However, management that exceeds these restrictions can cause exposure and erosion of peat soils and loss of the seed bank causing delayed regeneration (Legg et al., 1992). Furthermore, prescribed-burns that do not follow good practice guidelines (e.g. high wind speed, low fuel moisture) can escape and lead to more damaging wildfires (Marsden-Smedley and Sherriff, 2014).

Recommended rotation lengths have varied but are usually 8–25 years (i.e. 4–12.5% of the area burned annually) depending on vegetation type and individual site agreements. In some cases, the minimum height at which *Calluna* should be burned is given (e.g. 20 cm; Anon, 2011) and the practitioner is advised to base rotation lengths on how fast the vegetation grows, while in other cases specific rotation lengths are specified for particular substrates (e.g. 15–25 years on deep peat, unless heather grows particularly fast; Anon, 2007). In practice, in the UK uplands, it is impossible to apply prescribed-burning using fixed rules, mainly because of the rarity of consecutive dry days with relatively little wind when the vegetation is dry enough to ignite (Santana and Marrs, 2014, in review) but not too dry to burn safely. To some extent, the effective burning season has been extended through the recent development of "cool burning" or "pressurised fuel-assisted burning"; whereby a strip of vegetation at one end of the intended burn patch is sprayed with fuel such as petrol or diesel before ignition. This provides additional fuel to allow the fire to ignite and become sustained in vegetation with greater moisture levels, and hence can be implemented on a few more days each year.

The size of the prescribed-burn patch is also critical; the aim is to produce a mosaic of burn patches that are relatively small, with a maximum size of ca. 3000 m^2, i.e. 30 m x 100 m. The 30 m width is ideal for grouse production (implicit in Lovat, 1911), and is advised in the Heather and Grass Burning code (Anon, 2011), which suggests a maximum width of 55 m. Small burns are also considered to allow good fire control with limited manpower, indicating well-controlled practice that reduces the risk of prescribed-burns escaping and developing into wildfires, which cause far more damage. The general code, allows burns up to 10 ha (Anon, 2007), whilst some burning agreements specify an upper limit of 2 ha (Agreement Ref: AG00257049; Eyre, 2014).

Surprisingly, there is relatively little information about the scale and extent of prescribed-burning over time. In Scotland, an historical comparison (1940s–1980s) of burning across two areas showed clear geographical differences, with no burning at seven out of 32 sites in the southern sample area (Borders) yet only one of 32 in the northern area (Grampians) (Hester and Sydes, 1992). They showed that mean areas burned were similar in each region and that there was no evidence of a decline in burning activity since the 1940s. They also reported burning rates far below the 'optimum' (every 10–15 years) advised by the Muirburn Working Party (1997) for standard moorland with typical growth rates. In the English uplands, Yallop et al. (2006), also using aerial photography, assessed burning activity in the English uplands in 2000. They showed that 17% of ericaceous-dominated moor (mainly *Calluna*) was burned within the previous four years, with a median repeat burn time of 20 years. They also suggested an increase in area of very recent burns in a sub-set of sites within English National Parks from 15.1% to 29.7%. Douglas et al. (2015) found that burning increased between 2001 and 2011 using visual estimation of the percentage of moorland with burning patches.

Given the importance of careful management of these priority habitats and the contentious nature of the use of prescribed fire, it is surprising that there has been little attempt to assess management performance. This is partly due to the time and resources required to assess management on the ground. Here, therefore, we investigated the use of prescribed-burning on a single case-study estate (Howden Moor) in the Peak District National Park, Derbyshire over a 22-year period. Specifically we assessed whether prescribed-burning was producing: (1) burns covering agreed proportions of the moor, i.e. appropriate rotation lengths, and (2) burns of an appropriate size. We also assessed the probability of

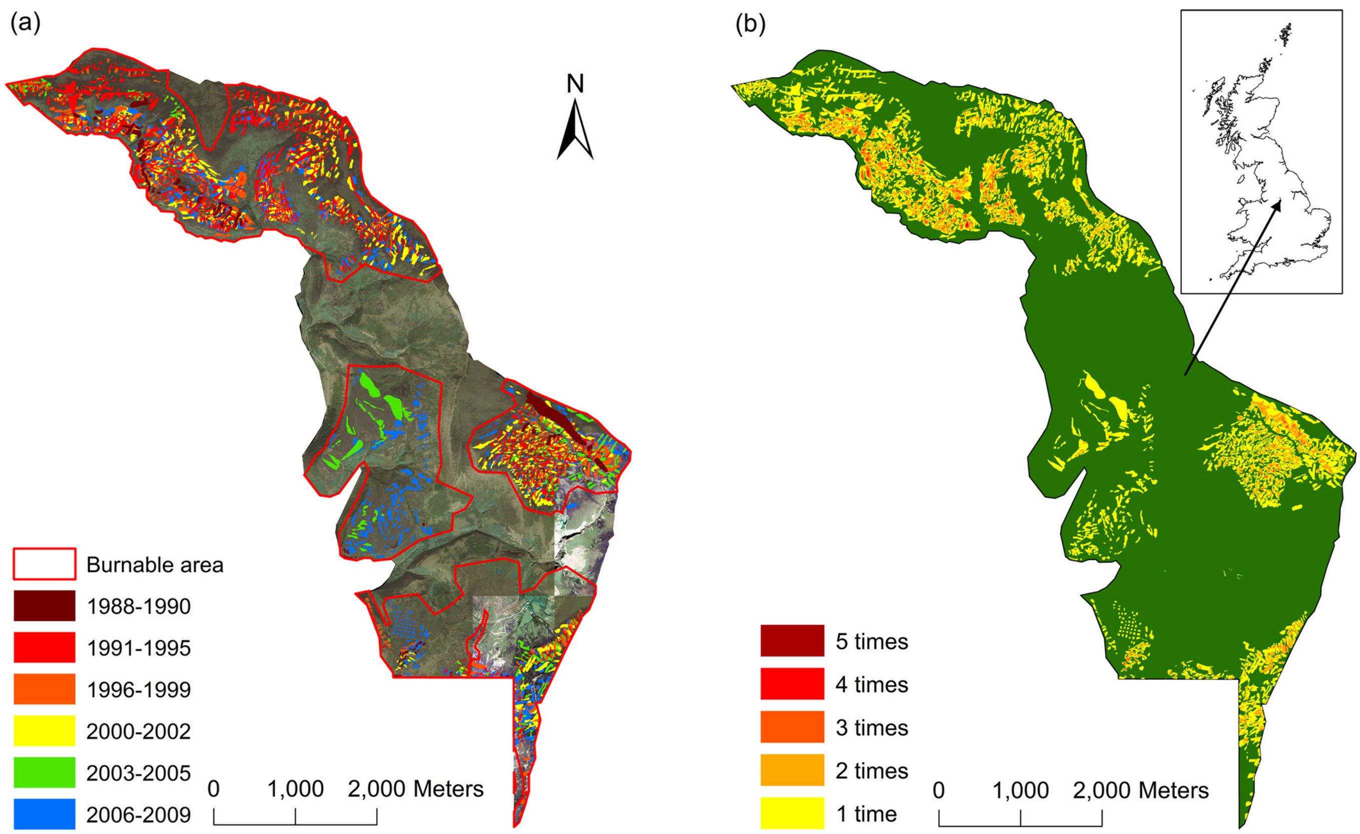

Fig. 1. (a) Map of prescribed burn patches on Howden Moor, Peak District between 1988 and 2009, overlain on aerial photography from 2005. Areas deemed burnable in the estate's burning plan are delineated in red. Some areas of the management unit have been excluded due to unavailability of aerial photography. B) Patches burned one, two, three, four and five times during the study period; green areas were not burned. Inset: location of Howden moor in UK.

a very large escape fire. We did this by digitising all the prescribed-burn patches on the estate using a combination of management maps corroborated with aerial photography for 1988–1999 and aerial photography for 2000–2009. The number and area of burns were then calculated for each time period to assess the use of prescribed-burning as an indicator of habitat condition and management standards. Whilst this method of monitoring should be widely useful across the UK and beyond, here it is focussed on one management unit, and the results should not be taken as indicative of moorland management anywhere other than this site.

2. Materials and methods

2.1. Study site

This study was carried out at Howden Moor, Derbyshire, UK (1.73 W, 53.44 N; Fig. 1). The moor is approximately 21 km^2, with elevation 246–546 m and slope 0–37°. The vegetation is dominated by *Calluna vulgaris-Eriophorum vaginatum* communities (M19/20 within the UK's National Vegetation Classification; Rodwell, 1991), growing on deep peat (>50 cm, Costigan et al., 2005; Harris et al., 2011a; Harris et al., 2011b) overlying millstone grit. While there is potential for functioning blanket bog (wet with peat-forming species including *Eriphorum* and *Sphagnum*) on this moor, there is very little currently 'active' (UKBAP, 2008) and the soil is generally dry. The climate can be described as severe by UK standards, with January and July mean temperatures of 3.2 and 15.6 °C and annual rainfall of 700 mm (UK Meteorological Office, Perry and Hollis, 2005).

The vegetation is particularly depauperate in this region, where a randomly-sampled, >1000 quadrat survey of five moors including Howden detected only 13 vascular plant species, six mosses and four lichens (Harris et al., 2011a; Harris et al., 2011b). *Sphagnum fallax* was the only *Sphagnum* species detected in extensive searches, and at very low frequency and cover, although some restoration work has been successful. This has been ascribed to past and present air pollution (Tallis, 1998; Caporn and Emmett, 2009). Although air quality has improved over the last fifty years, nitrogen deposition at Howden exceeds the critical load (CL) for moorlands (Howden deposition = 30 kg N ha^{-1} yr^{-1}; Moorlands CL = 5–10 kg N ha^{-1} yr^{-1}; Bealey et al., 2003). Management includes prescribed-burning for grouse production, sheep grazing and restoration efforts to change *Molinia caerulea* (L.) Moench-dominated vegetation to *Calluna*-dominated (Anderson and Radford, 1993).

At the start of this study period, the Environmentally Sensitive Area prescriptions were just beginning. The burning plan agreed with statutory agencies recommended that 7% of the burnable moorland area (at that time the entire moor was included) should be burned annually, i.e. on an average 15-year rotation interval. *Calluna* grows quickly on this moor (mean age at 25–35 cm = 10 ± 0.4 years, R H Marrs, unpublished data) and it was identified that there was "a large backlog of burnable heather" due to several years of bad weather (Starbuck and Harris, 1991; within Eyre, 2014). Because of this backlog, the annual burn target was then increased to 10% of the moor. There is no functioning blanket bog on this moor, so no large areas were excluded from burning. However, at a small-scale, areas with steep slopes were omitted as they are prone to erosion if soil is exposed and pose greater difficulties in fire control. Areas covered with dense *Molinia* were also excluded from routine burning; although some areas were burned to re-establish *Calluna*. The implemented burning has been concentrated into four main areas forming the "potentially burnable area" (partly through changing

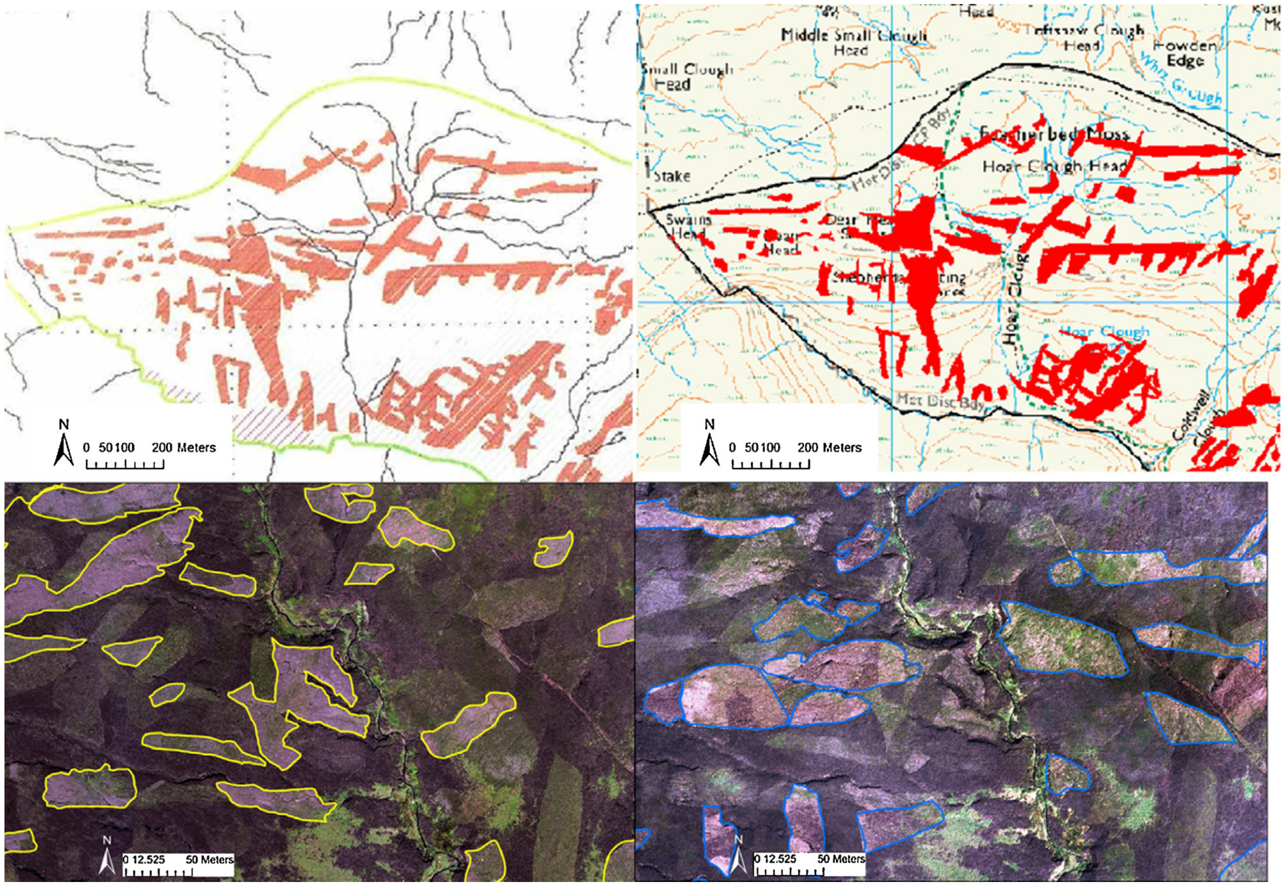

Fig. 2. Part of an estate burn map for Howden Moor between 1991 and 1995 (top left), and its digitised equivalent (top right). Aerial photographs illustrating the importance of considering previous burn history in interpreting later photographs; yellow boundaries illustrate patches identifiable on the 2005 photograph (bottom left): blue illustrates additional patches identifiable on the 2009 photograph (bottom right). Top and bottom panels show different areas of the moor.

conservation policies) and the remaining area left unburned (Fig. 1), inevitably leading to variable rotation lengths across the entire moor.

2.2. Number and area of prescribed-burn patches

All GIS analyses were conducted using ArcMap 10.0 (ESRI, 2011). Prescribed-burning between 1988 and 2009 on Howden Moor was assessed using a combination of detailed estate burning maps and aerial photography. Estate maps showing prescribed-burning records were available for three time periods (1988–1991, 1991–1995, 1996–1999) and were digitised directly using GIS (Fig. 2). Geo-referenced aerial photography was available for 1999, 2002, 2005 and 2009 from Landmap (Anon, 2013). Using these images, all burn scars were identified visually and their outlines digitised to produce maps of burn patches in three time periods (2000–2002, 2003–2005 and 2006–2009). The 1999 aerial photograph was also used to cross-validate burn patches digitised from estate maps. In the case of the pre-1999 records, most mapped burns were still visible on the aerial photograph, and the location and extent of the mapped burn could be verified and corrected; the photograph used for spatial extent and the map used for dating. During digitising, the layer of burned patches from the previous time period was cross-referenced to ensure only more recent burns were included (Fig. 2). The following information was then extracted from the GIS for each time period:

1. Number of burn patches.
2. Area of each burn patch.
3. Overlap of burn patches in different time periods, indicating multiple fires at a single location. These areas are hereafter referred to as "repeat-burned areas".

This information was used to calculate both the "sum of burn patch areas" across all years (including repeat-burned areas additively) and the 'area exposed to burning' across all years (representing the area of ground burned at least once during the entire study period, irrespective of the number of successive burns at any one point). The area of prescribed-burns in each period was also calculated as a percentage of both the entire moor area, and the area that was realistically available for prescribed-burning. This "potentially burnable" area excludes those parts of the moor where prescribed-burning was unlikely to be used; i.e. because of their topography (valley sides), substrate (rocky outcrops), or vegetation composition (areas dominated by graminoids and subject to ongoing restoration work). The "potentially burnable" area does include areas of *Calluna*-dominated moorland that were not burned; this is because some areas have been left unburned to provide long-rotation stands of vegetation, as is required in most modern burning plans (Anon, 2007).

2.3. Statistical analysis

Most of the data were analysed using simple descriptive statistics. In addition, the numbers of burn patches in each time period, and in the overall 22-year period, were plotted in size-rank order against patch size. A 3-parameter asymptotic relationship was fitted (other equations were tested with very similar results) for all

Table 1

The number and area of the burn scars produced by prescribed burning on Howden Moor, Derbyshire in six time periods between 1988 and 2009 (a) descriptive data, (b) as a percentage of the moorland area and percentage of the moorland area per year. The potentially burnable area is the total moor area minus areas where burning is restricted or not desired. The area measurements do not account for areas burned more than once in different time periods hence underestimate burning activity. The areas of *Molinia caerulea*-dominated land that were burned within a designed restoration programme outside normal moorland management are included in the totals but have also been identified separately. The percentage has been calculated on both a whole moor and "potentially-burnable" area basis; percentages in parentheses have been re-calculated to exclude the *M. caerulea* restoration burning. Superscript "c" indicates sum of burn patch areas across all years (or derived values) and "d" area exposed to burning (see text).

Variables		Sampling period						All years	
		1988–1990	1991–1995	1996–1999	2000–2002	2003–2005	2006–2009	Total	Mean
Number of years		3	5	4	3	3	4	22	
Number of burns		61	716	555	498	201	530	2561	116 per year
Area of burns (m^2)	Total area	310,000	1,290,000	847,000	1,020,000	531,000	137,000	5,370,000^c 4,160,000^d	
	Annual area	103,000	259,000	212,000	342,000	177,000	342,000	244,000^c	
	Mean patch size ± SE	5080 ± 1780	1800 ± 80	1530 ± 85	2060 ± 94	2640 ± 284	2580 ± 141	–	2098 ± 67
	Minimum size	403	33	70	57	106	57	33	–
	Maximum Size	110,000	23,500	18,700	16,300	38,000	34,700	110,000	–
	Molinia-restoration fires	–	–	–	–	74,300	34,600	–	–

Sampling period	Entire moor (20.9 km^2)		"Potentially burnable" (14.4 km^2)	
	% of area	% of the area per year	% of area	% of the area per year
1988–1990	1.5	0.5	2.1	0.7
1991–1995	6.2	1.2	9.0	1.8
1996–1999	4.1	1.0	5.9	1.5
2000–2002	4.9	1.6	7.1	2.4
2003–2005	2.5(2.4)	0.8(0.8)	3.7(3.4)	1.2(1.1)
2006–2009	6.5(6.4)	1.6(1.6)	9.5(9.3)	2.4(2.3)
All years^d	19.9	0.9	28.9	1.3

years and each time period using the nonlinear least squares (nls) function within the R statistical Environment (R Core Team, 2013).

3. Results

3.1. Area burned

The distribution of all prescribed-burn patches in relation to the entire moor and the "potentially-burnable" area is shown in Fig. 1. Over the 22-year period 4.16×10^6 m^2 was burned at least once, equating to 20% of the entire moorland area or 29% of the "potentially-burnable" area (Table 1). The remaining 80% of the entire moor area or 71% of the "potentially-burnable" area was unburned throughout the period. The sum of all burn patch areas (including repeat-burned areas) was 5.37×10^6 m^2. The annual area burned fluctuated between 0.10 and 0.34×10^6 m^2, with greatest activity between 2006 and 2009 when ca, 1.37×10^6 m^2 was burned in total (Table 1a). This equates to between 0.5 and 1.6% of the entire moor area per year or between 0.7 and 2.4% of the "potentially-burnable" area per year (Table 1b).

3.2. Number and size-distribution of prescribed-burns

In total, 2561 prescribed-burn patches were detected, with the greatest number between 1991 and 1995 (716 patches) and between 61 and 555 prescribed-burn patches in the other time periods (Table 1a). The mean (±se) patch size over the entire 22-year period was 2098 ± 67 m^2 (Table 1a), but the size-distribution was skewed heavily towards small patches (Fig. 3). Nevertheless, there were some patches in each time period that were much larger than the mean, with the largest one at almost 109,718 m^2 between 1988 and 1990. Since this early period the maximum size has reduced with only three burn patches identified greater than 20,000 m^2; two between 2003 and 2005 (37,880 and 36,478 m^2) and one between 2006 and 2009 (34,656 m^2). Thus, the maximum patch size has reduced by 68% over the study period.

3.3. Areas of successive burning

Some areas were burned more than once during the study period (repeat-burned areas); in total 0.96×10^6 m^2 was burned twice, 0.13×10^6 m^2 burned thrice, 8292 m^2 four times and 260 m^2 burned five times; no patch was burned six times. Patterns of repeated burning of some areas (Fig. 4) show inevitably that patches burned in earlier time periods were more likely to be burned again than patches that were first burned in later years. Fifty-nine per cent of the 1988–1990 burned area was burned at least twice. Approximately 13% of burns by area were in vegetation burned less than 10 years previously (within the date range of this study), although we cannot be certain of the exact year of burns within the 3–5-year sampling periods.

3.4. Relationship between proportion of burned patches and burn size

There was rapid increase in the cumulative proportion of land burned in the small patch-size categories approaching an asymptote at ca. 10,000 m^2, with essentially more or less the same response over all time periods (Fig. 5). The size of burned patches that were within the 95, and 99 percentiles were calculated from the overall equation as 6,464 and 14,835 m^2, respectively. Hence, 5% of fires were more than 6500 m^2 and less than 1% greater than 15,000 m^2. This assumes that the burn patches were all created individually, whereas in reality at least some were created by burning into existing patches (Fig. 2). Thus, these are over-estimates of the actual sizes associated with these probabilities.

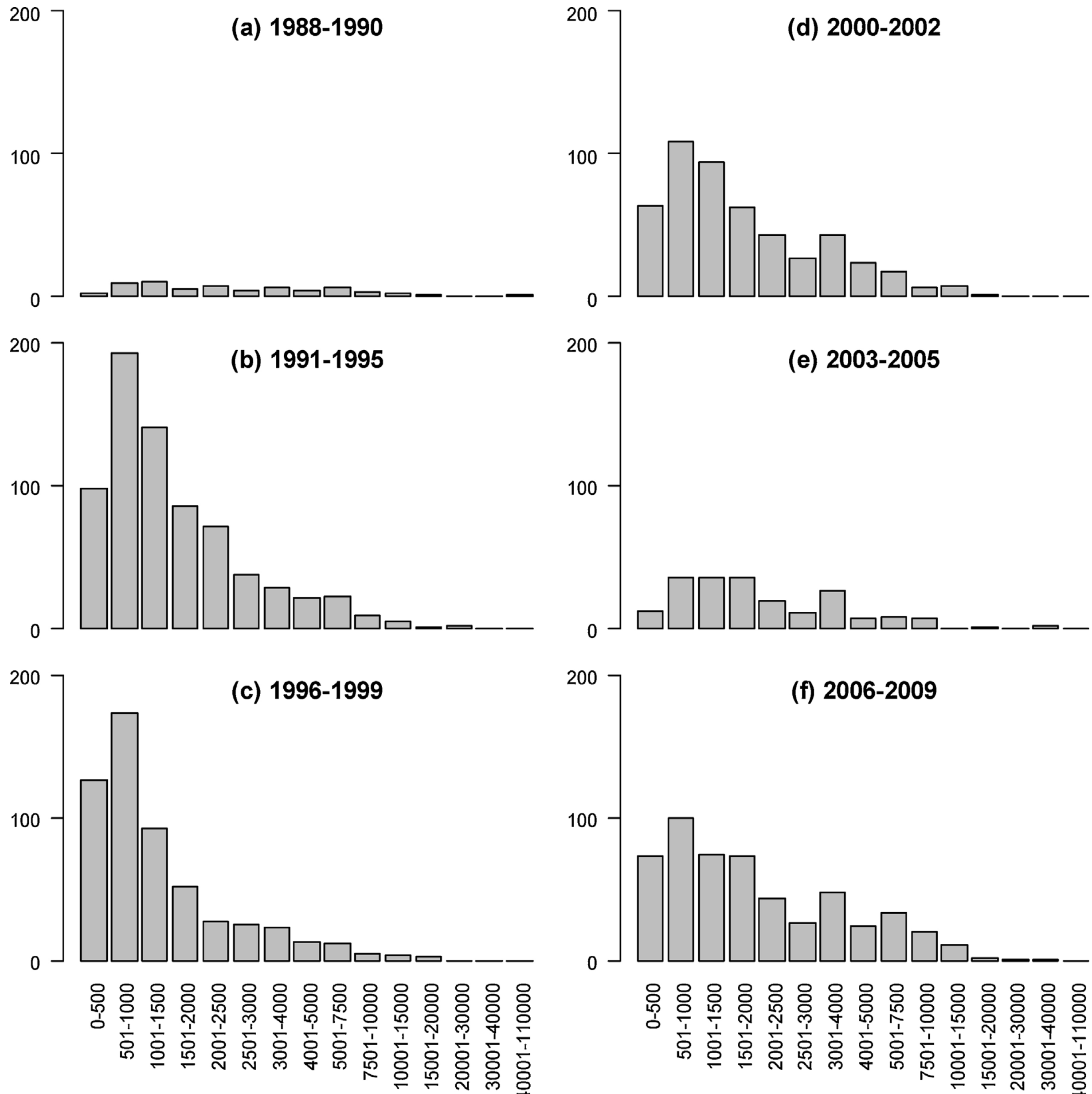

Fig. 3. Number of burn patches by size class (m^2) on five sampling occasions between 1988 and 2009 at Howden Moor, Peak District.

4. Discussion

Prescribed-burning on moorlands is a contentious contemporary issue (Bain et al., 2011) and there is currently insufficient evidence on which to base good practice guidelines in the interests of both conservation and preservation of ecosystem services. However, in the UK, most burning of moorland vegetation requires consent from a statutory agency and much is covered within Agri-Environment schemes such as Environmentally Sensitive Areas (ESA) and Countryside\Environmental Stewardship (Anon, 2002; Anon, 2014). Codes of good burning practice exist but there is continued concern that they are not adhered to and that prescribed fires will escape. This could lead to wildfires over very large areas and potential damage to sensitive habitats designated as no-burn areas. Moreover, weather and terrain constraints make some parts of compliance difficult, especially with respect to annual burn-area quotas. In some years almost no burning is possible and in others, when the conditions are favourable, there may be intense activity. The obvious way for both conservation agencies and managers to make sure prescribed-burning is implemented under required permissions and good-practice codes is to monitor performance. In this study, we have attempted to do this for a single, case-study site in the Peak District in Derbyshire using estate maps and aerial photographs. The burn maps were created through a combination of the estate owner's interest in ecological moorland management and requirements for compliance with agri-environment schemes in the early 1990s. Having these maps allowed us to extend our study period beyond that for which aerial photography was available, however it would be possible to conduct this type of analysis using aerial photography alone. While the specific results obtained for this management unit cannot be extrapolated to any other sites, and we do not claim that management on this moor is characteristic of UK moors in general, the method for monitoring proved to be effective. Six important results were obtained, these were:

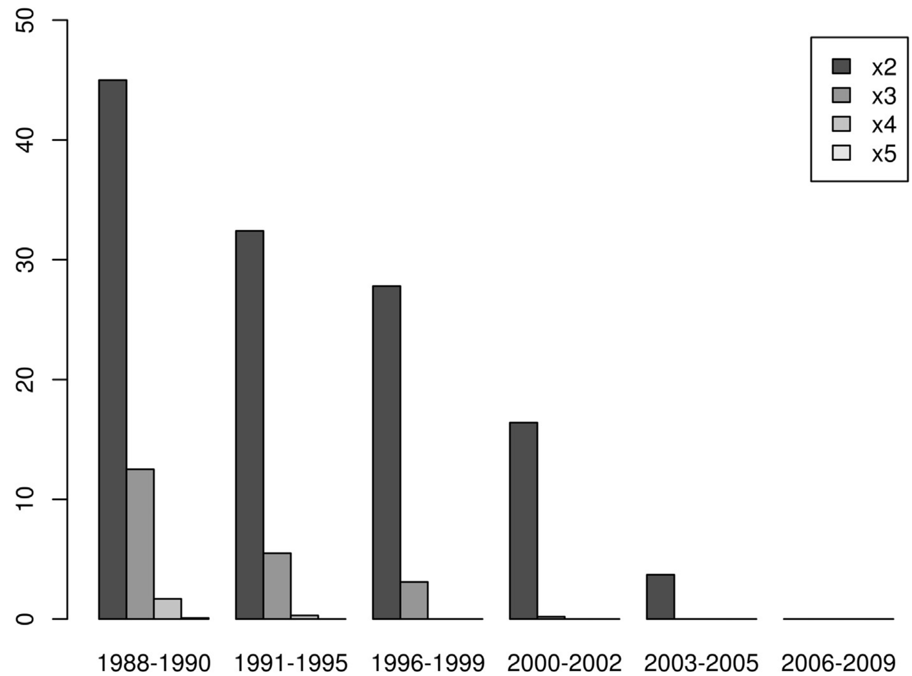

Fig. 4. Percentage of burned area that was subsequently burned again (repeat-burned areas). Areas burned two, three, four and five times are shown separately by period of first burning. No patch was burned in all 6 periods.

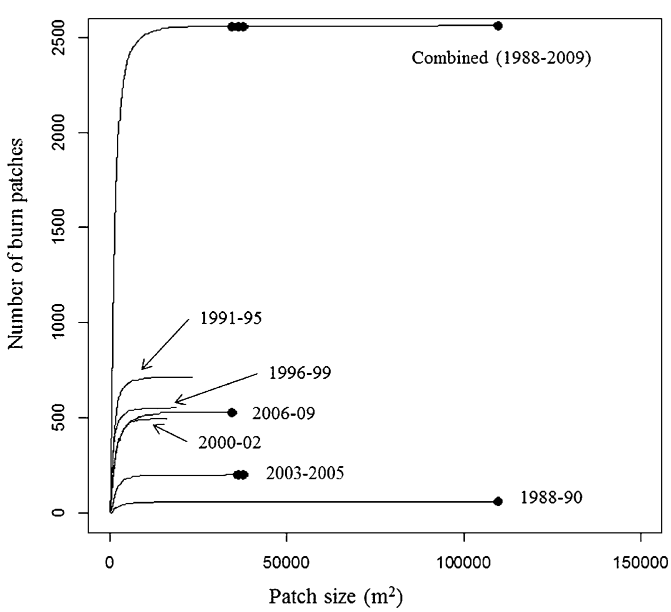

Fig. 5. Number of burn patches (rank order) with respect to burn patch area in each of six time periods between 1998 and 2009 and all data combined. Very large burns (>30,000m^2) are denoted with filled circles. Fitted equation: $Y = 2503 - [401.9 \times \exp(-7.322 \times X])$.

1. Aerial photography provided an effective tool for monitoring prescribed-burning management.
2. The annual area burned on Howden Moor (0.9% per year) was far below the current amount recommended generally by the statutory conservation agency (10% per year) or for this moor originally (7%).
3. Greater than 70% of the "potentially-burnable" area remained unburned.
4. There was some evidence for a general increase in the annual area burned since 1988, but it has fluctuated through time.
5. Burn patches are in keeping with the target sizes specified by best practice guidelines.
6. The risk of a large or escaped fire was very low on this moor and no incidents requiring Fire and Rescue Service assistance occurred during the study period.

Over most of this study period, the statutory agencies' recommendations for these Peak District moorlands were that 7% of the burnable moorland area should be burned annually, i.e. on a 15-year rotation interval, accepting that some areas remain unburned (Starbuck and Harris, 1991; within Eyre, 2014). Actual burning rates on Howden moor over the last three decades were far below this recommendation, with only 0.7–2.4% of the potentially-burnable area burned annually on average (0.5–1.6% of the entire moor). These values equate to overall moorland rotation intervals of 142–42 and 200–63 years, respectively. This is in keeping with the findings of Hester and Sydes (1992) for moorlands in Scotland (1992; 1–2% yr^{-1}), although Yallop et al. (2006) reported levels of >4% yr^{-1} in some ericaceous moorland. Some conservation agencies have called for longer rotations or complete cessation of burning (e.g. RSPB, 2015; SNH, 2015), primarily to conserve carbon, but Allen et al. (2013) suggested that rotations in the range 8–18 years (12.5–5.5% burned annually) would minimise carbon loss from above-ground vegetation.

Given the annual area burned in this study it seems that, in practice, burning is unlikely to exceed the originally recommended annual maximum for this moor of 7%, and that increased rotation intervals may be impossible to implement. At the start of the period reported here, the ESA prescriptions were just beginning and the intention was to burn on a 15-year cycle (6.7% annual area burned). This requirement identified that there was "a large backlog of burnable heather" and that there were constraints on available burning time, i.e. "1990/1991 was another difficult burning year with nearly all activity confined to the last 3–4 weeks up to the middle of April [the end of the legal burning period]" (Starbuck and Harris, 1991; within Eyre, 2014). Prescribed-burning activity increased during the 1990s to meet these targets. Indeed, by 1991 and 1995, "an average of 4% of heather moorland was burned annually on agreement land in comparison with just 1% in 1988/9" (Allen, 1997; within Eyre, 2014). The number of burns within the different time periods was variable, but there is some evidence for a small increase in burning activity since 1988 on this moor. Yallop et al. (2006), raised concern about the increased burning activity during this period, however in this study, annual areas burned remained below recommendations. Thus, concerns about area of moorland burned annually seem to be unwarranted on this moor, where good practice was adhered to in terms of patch size and weather/date constraints, as managers were unable to achieve the burned area required at the time. Furthermore, Harris et al. (2011a, 2011b) showed that management practice on this moor does not remove all above ground biomass, therefore protecting underlying peat, and leads to good regeneration of the vegetation.

Moreover, an increase towards recommended burning rates, applied across a wider area and in older vegetation, could be viewed positively under the assumption that some burning is necessary to maintain moorlands in their mid-successional state, prevent conversion to woodland and preserve ecosystem services. Moorlands are valued as cultural landscapes and have been maintained by humans for centuries (Gimingham, 1972). Without management, much UK moorland would eventually revert to woodland (Miles, 1979) (on Howden Moor, *Betula* spp., and *Pinus sylvestris* are colonising the fringes), which may be preferred in terms of carbon storage and other ecosystem services, but would lose the cultural value specific to moorland, as well as the potential biodiversity. Fire plays an important role in the maintenance of moorlands, as the vegetation is fire-adapted and *Calluna* shows increased regeneration from seed in response to fire (e.g. Måren et al., 2010). Management by cutting is also possible, although more expensive and the use of machinery can damage fragile peat soils. Wildfire risk is only reduced if cut vegetation is removed from the site, and carbon emissions only prevented if it is not subsequently burned or decomposed. Grazing may also be used, but if pressure is too high, species composition can move from dwarf-shrub- to graminoid-dominated vegetation, changing its conservation value (Anderson and Yalden, 1981). Prescribed-burning may, therefore, be the most cost-effective tool for maintaining moorland ecosystems.

The majority of burn patches on this moor throughout the study period were within the 501–1000 m^2 size class (Fig. 3) indicating that patches were in keeping with the target sizes used by land managers burning for grouse (Hester and Sydes, 1992). Only four large burn patches were noted over the 20 years. The largest, at almost 110,000 m^2, was the only fire greater than the maximum single burn size of 10 ha (Anon, 2007) and the only escape fire to have occurred. This was in the earliest period. According to the estate manager in charge of the fire "This fire was one of the first in that area and skipped a fire break and jumped into an area with long degenerate *Calluna*. The wind changed and strengthened and the fire extended to a much larger area than intended. This fire took six hours to get under control mainly because of re-lights within the burned area" (G. Eyre, pers. comm.). The three other large burn patches were not on *Calluna*- but on *Molinia*-dominated land. Patch sizes were intended to be large as they were designed to burn off large areas of *Molinia* as part of a moorland vegetation restoration scheme (Marrs et al., 2004). Moreover, whilst they appear as single patches on remotely-sensed imagery, they were implemented through a series of smaller, contiguous fires over a period of several days. The reported areas and percentages burned in each time period are, therefore, overestimates if these three large restoration fires are excluded (Table 1).

One reason for the overall adherence to size restrictions of most prescribed-burns on this moor is that there have been substantial improvements to prescribed-burning practice over the last 20 years, which helps reduce the risk of fires getting out of control. Most practitioners now routinely have access to protective clothing and use ATV-vehicles to cut fire-breaks before lighting fires; these provide an additional point where the fire can be stopped. They also usually have a "Fire-fogger" (http://www.firefighting.co.uk/) or similar technology on site, in addition to hand-held, traditional fire-floggers for controlling and extinguishing fires. Furthermore, "cool burning" or "pressurised fuel assisted burning" is increasingly used, rather than traditional techniques which required the vegetation to be relatively dry before a fire could be sustained. With this new approach, the vegetation is sprayed with liquid fuel before ignition, with the result that fires can be lit when the vegetation has a greater moisture content; which has two advantages. First, the manager can burn outside the very few series of rain-free days that are needed to achieve a sufficiently low moisture content for traditional burning. Second, because there is more available time there is less pressure to burn when the safety limits for preventing escape fires are approached (vegetation becoming too dry, wind speed increasing, etc.). On this case-study moor, the Fire and Rescue Services have never been called out for fire control, although suppression of one escape fire was undertaken by estate staff, which may be considered a wildfire (Scottish Government, 2013). However, with the increasing use of these new technologies since 1991, all fires have been close to intended target ranges. Indeed, we estimated only a 1 in 20 chance of producing a fire greater than 6,464 m^2 and a 1 in 100 chance of producing one greater than 14,835 m^2, and this is an over-estimate as the calculations included the three fires that were designed to be larger for restoration management. Translated into realistic patch dimensions, 6,464 m^2 equates to a patch 81×81 m^2 if square (or 30×215 m^2/50×129 m^2 if rectangular) and 14,835 m^2 to 122 x 122 m^2 (30×495 m^2/50×296 m^2).

An important result here was that many patches were burned more than once, indeed some areas were burned five times within the 21 years (260 m^2 equating to 6×10^{-5}% of the area exposed to burning; Fig. 1b), essentially on an approximate 4-year rotation. This is at a greater frequency than usually recommend, but concerns a relatively small area, with 14.3 ha burned 3 or more times. This may have resulted from (a) burning of adjacent patches into existing burned vegetation, or (b) a need to burn at a greater frequency because of the very high growth rates of *Calluna* in this region (R H Marrs, unpublished data; Eyre, pers. comm.). Approximately 13% of burns by area were in vegetation less than 10 years old. While burning young *Calluna* on short rotations may promote diversity within that patch (Harris et al., 2011a), it will not promote overall moorland biodiversity, as large areas of unburned, degenerate *Calluna* will remain, forming a virtual monoculture. This may also be detrimental to fuel load reduction, one of the main aims of modern prescribed-burning, because where large areas remain unburned biomass will increase considerably (Allen et al., 2013). This study showed that 29% of the total burnable area was burned, leaving the rest unmanaged and accumulating fuel. In order to address this, future recommendations might include guidance on application of prescribed-burning across the range of *Calluna* growth phases (Watt, 1947, 1955) or even a preference for burning older stands. This could be achieved using larger fires, which require less manpower and therefore cost per unit area. Large fires are not preferred when managing for grouse, but areas with degenerate heather are not being actively managed, so this may be of less concern. However, excessively large fires can generate greater fire intensity and severity, causing ecosystem services to be temporarily reduced, and can also be more difficult to control. Nevertheless, this needs to be set against the risk of severe wildfire in high fuel loads and loss of habitat/biodiversity through successional changes.

Whatever future guidelines recommend, it is important that measures are available to monitor the application of prescribed-burning and ensure that good-practice guidelines are adhered to. This study shows that interpretation of aerial photography through time is an effective monitoring method. It allows assessment of the location, area and quantity of prescribed-burns and comparison with the mapped records of the land owners. The process could be partially automated by using GIS classification methods to identify burn scars, which would reduce human effort significantly. In order for monitoring to be accurate and effective, aerial imagery would need to be taken at least every 3–4 years. Beyond this time, visual differences in patch delineation become more difficult to detect and dating errors may increase. The information derived from such monitoring studies should give stakeholders in moorland landscapes greater understanding of the standards at which prescribed-burning is applied and the level of adherence to good-practice guidelines, allowing them to adjust management that does not meet the criteria. This will allow preservation of both biodiversity benefits and provision of ecosystem services.

Acknowledgements

We thank Biodiversa (NERC/DEFRA: grant number NE/G002096/1) and the Heather Trust for financial support and Geoff Eyre for permission to work on Howden Moor and historic management maps. Pierre Denelle was supported by an ERASMUS student traineeship and we benefited from preliminary work by Matt O'Connor during a Nuffield Research Placement.

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