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Resolving a heated debate: the utility of prescribed burning as a management tool for biodiversity on lowland heath.

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Abstract

1. Lowland heath is a priority habitat for conservation, nowadays largely managed for biodiversity. Historically, prescribed burning has been the principal management tool, but there are increasing calls to substitute burning with cutting to improve biodiversity outcomes. However, poor understanding of potential impacts compromises decision making.

2. Our study was carried out in the New Forest National Park, the largest area of lowland heath in Europe. Using a multi-trophic approach, we compared the ecological impact of prescribed burning with two types of vegetation cutting (swiping and baling) as management tools for biodiversity outcomes for up to 20 years after management. Indicators included: Common Standards Monitoring assessment (CSM); vegetation species assemblage; below and above ground invertebrate biodiversity; and available food resources for two characteristic heathland birds - the Dartford Warbler *Sylvia undata* and the Nightjar *Caprimulgus europaeus*.

3. When compared with swiped sites, areas managed by prescribed burning resulted in: better habitat condition (assessed by CSM); higher cover of heathers; lower bracken cover; more areas of bare ground. We found no evidence that burning is detrimental for the investigated components of biodiversity.

4. Cutting by swiping did not replicate the benefits of burning. Swiping supported grassland conditions that suit non-heathland species. Baling resulted in habitat condition similar to prescribed burning, but restricted replication of baled sites limited our conclusions. However, swiped sites supported high invertebrate abundance and diversity, including food resources for Dartford Warbler and Nightjar.

5. *Synthesis and applications*

Removing burning from the management programme is likely to reduce Heathland Condition. Biodiversity is encouraged by a mosaic of management and more mobile species, such as birds, will exploit the resources provided by several management techniques. Including some cutting in a rotational regime is likely to be beneficial although prescribed burning should form the majority of the management programme, Lowland heathland differs fundamentally from upland heathland/moorland and it is not easy to transfer the results. Current heathland Common Standards Monitoring assessment does not adequately assess wider biodiversity on protected areas but is effectively an assessment of vegetation feature condition. Including invertebrates in surveys provides a more nuanced assessment of heathland condition.

Introduction

British heathlands are semi-natural landscapes that evolved on nutrient poor, usually acidic soils through the removal of nutrients and biomass, largely developing after anthropogenic Neolithic forest clearances. They are characterised by dwarf shrub communities, dominated by *Calluna vulgari*s, varying in species composition along an altitudinal gradient from upland moorland to lowland heath (<300 m elevation; <1000 mm annual precipitation; Webb, 2008, Elkington *et al.*, 2013). From the medieval period, most heaths in Britain were managed as commons on which local people had the right to graze animals, gather herbage and fodder, practice turbary (turf cutting), and collect peat and wood for fuel. Small areas were periodically burnt to provide nutritious forage, and heather was cut as winter fodder for cattle. These activities maintained an open landscape dominated by dwarf ericaceous shrubs that supported unique and valuable communities of flora, invertebrates, reptiles and birds (Webb, 2008).

In the UK, as in the rest of Europe, traditional uses of heathland declined from the 1930s onwards, many heaths becoming fragmented as land was converted to arable agriculture or used for urban development. Heathland habitat became rare, thereby threatening heathland specialist species. Since 1981, lowland heath has been listed under Annex 1 of the EU Habitats Directive and is a priority habitat under the UK Biodiversity Action Plan; it is currently proactively managed to conserve the characteristic habitat as an end in itself. The UK contains an internationally significant proportion of dry heathland, supporting approximately 18% of the world total, of which 95,000 ha (11%) is lowland heath (Townshend *et al.*, 2008).

With heathlands managed as conservation landscapes, rather than working landscapes, the manner of their management has opened to public debate. Prescribed burning, the '*Controlled application of fire to vegetation in either their natural or modified state, under specified environmental conditions which allow the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to attain planned resource management objectives'* (FAO, 2003), has become a contentious management tool. Although rotational burning was used traditionally, albeit varying in extent and frequency across the heathland range (Webb, 2008), concerns have been raised that burning results in poor environmental outcomes by negatively affecting water quality, carbon dynamics and habitat composition (Harper *et al.*, 2018). There has been particular concern expressed for amphibians and reptiles, but the impact of prescribed burning on these species – especially in the UK - remains poorly understood. While extensive summer burns can directly kill large numbers through exposure to fire and loss of cover post fire, cold, winter burning in modest patch sizes is likely to have the lowest impact, as the temperature is unlikely to penetrate the soil to the hibernating animals and the distance for habitat re-colonisation will be low (Jofré and Reading, 2012; Santos et al., 2022).

In contrast to fire-prone regions, where wildfires are key drivers for environmental outcomes, the impacts in temperate regions (where the majority of heathland burning is prescribed), are poorly researched (Newton *et al.*, 2009). This paper aims to fill that gap in evidence-based decision making.

In the UK, decision making over the use of prescribed burning is further compromised by an increasingly polarised and heated debate. The dispute originates in upland areas, where rotational prescribed burning is traditionally used to create a mosaic of differently aged heather to benefit red-grouse (Harper *et al.*, 2018), hence, much of the UK heathland management debate is enmeshed with conflict over grouse management. Burning management for grouse has a different objective in terms of the type of vegetation required; more frequent burning is conducted to maintain a supply of young shoots. Burning is conducted when heather is 20-30 cm high, typically 8 years on the most fertile soils, longer on less productive ones. In contrast, in the New Forest (NF) it is to prevent scrub developing and maintain grazing for commoners' livestock and thus conducted on a 20-year rotation. Despite the difference in management targets, the debate is being driven as much by political and economic interests as ecological understanding and consequently, and crucially, it lacks nuance, even though the limited evidence available demonstrates spatial heterogeneity in burning practices and comprises examples of both good and bad practice (Davies et al., 2016). Furthermore, the majority of research into prescribed burning has been carried out on upland systems where driven grouse shooting is contested (comprising 77% of the evidence base (Harper *et al.*, 2018). Davies *et al.*, 2016 further suggest that the tone of the debate inhibits necessary research by discouraging land managers collaborating when "the prevailing public perception of fire is negative and managers are inclined to view scientists as having an agenda". This perception compromises research in lowland areas too. Furthermore, the Common Standards Monitoring protocol is restricted to vegetation, thus encouraging a one-dimensional focus on this as the indicator of habitat quality. As a result, there is a paucity of evidence of the broader ecological effects of prescribed burning, yet there remains an urgent need for scientific evidence to inform land managers and policy makers on the management of lowland heathland, as it differs fundamentally from upland heathland/moorland. Lowland heathland occurs below 300 m on sands and gravels and has a higher floral diversity compared to upland heathland which is on shallow peat and mineral soils, Consequently, the impact of management interventions may not always be directly comparable.

Our study area was the New Forest National Park, the largest area of remaining lowland heath in Europe (McLeod *et al.*, 2005), containing approximately 14,600 ha of heathland and similar habitats (Tubbs, 1974). The national park is an IUCN-designated category V protected area ('Protected Landscape'; Chape *et al.*, 2005). It is covered by four designations: Site of Special Scientific Interest (SSSI), Special Area of Conservation (SAC), Special Protection Area for birds (SPA) and Ramsar, and has a targeted Biodiversity Action Plan (BAP). The New Forest landscape is characterised by a mosaic of *Calluna vulgaris* dominated heathland, unimproved grassland and woodland, maintained through proactive heathland management in the form of prescribed burning or cutting and modified by grazing. The area is extensively grazed by ponies and cattle under New Forest commoners' rights.

Delivering the New Forest Protected Areas status is facilitated via a local partnership representing diverse stakeholders. With these diverse bodies and the presence of an engaged and vocal community, there is need for a coherent evidence base to inform consistent New Forest management decisions.

The aim of our research was to compare the ecological impact of prescribed burning with vegetation cutting (i.e. the principal alternatives of swiping and baling) as management tools for biodiversity outcomes, taking a multi-trophic approach. We employed standardised methods, repeatable, locally tailored but with global relevance and gathered a large quantity of data to ensure the rigour of our results.

Materials and Methods

Current management practice

Prescribed burning is carried out in the New Forest on an average rotation of 23 years. Approximately 400 ha across roughly 159 sites are burnt annually by the Forestry Commission (Dave Morris, Forestry Commission *Pers. Comm.*). The management programme is agreed with stakeholders including the Commoners Defence Association and Natural England. Alongside prescribed burning there is also a cutting programme. 'Cutting' can mean swiping (i.e. cutting with a flail and leaving the litter) or heather baling. Cutting is not as widely used as prescribed burning in the New Forest, making up a smaller component of the overall seasonal programme, typically comprising approximately 10% of management each year (Dave Morris, *Pers. Comm.*). The Forestry Commission maintain records of all management that takes place in the New Forest. These records enabled us to identify a replicated chronosequence of sites to investigate impacts of the management techniques in both time and space.

Sampling design

One hundred and five sites were selected in a replicated, three block design (See Fig.1) across the New Forest National Park. Each block comprised three replicate sites each of swiped and burnt areas in a chronosequence of 0, 1, 6, 10 and 20 years after management. Because of the small number of baled sites, it was not possible to fully incorporate baling into the experimental design. In each block we identified one replicate of each of five sites between the ages of 0 (newly baled) and 12 years. These were not included in main analyses but used as supporting information.

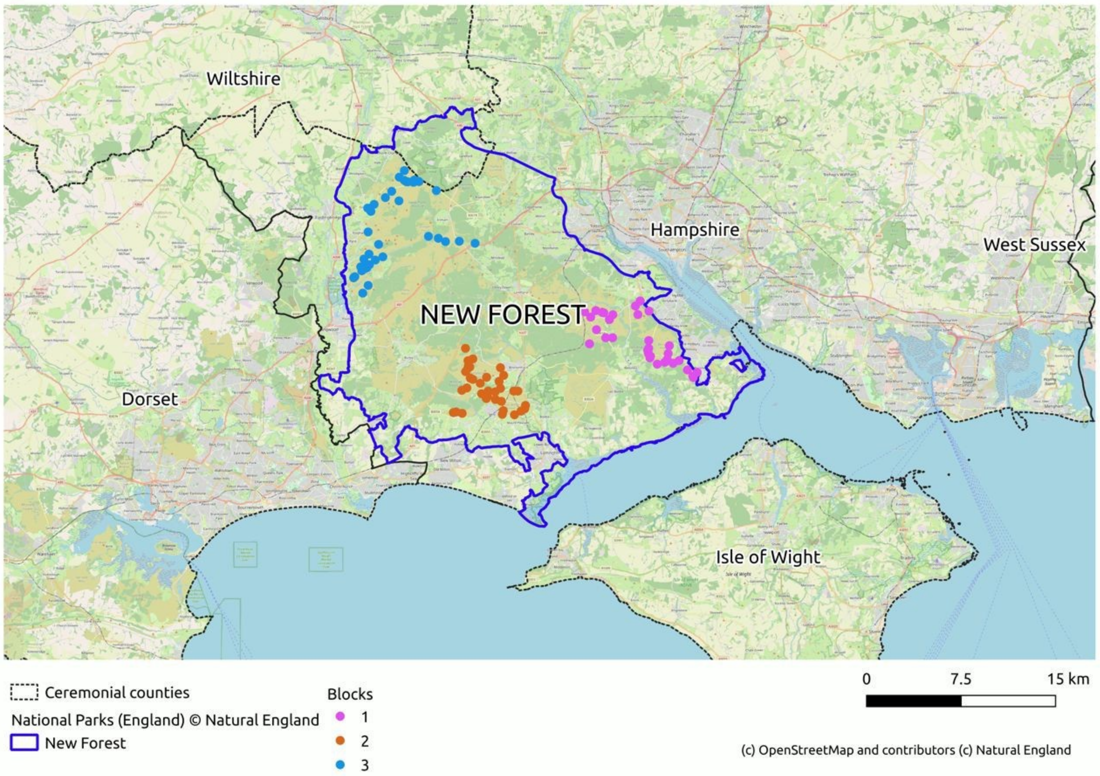

Fig. 1: Position of the New Forest, Hampshire, in Southern England. Each dot represents a sampling location. Experimental blocks 1,2 and 3 are coloured pink, brown and blue respectively. Within each block are: three replicate chronosequences (0, 1,6,10 and 20 years) burnt and swiped sites; one replicate of 0,1, 6,10 and 12 years baled sites.

Sampling and sample identification was carried out by 42 volunteers, recruited and trained by staff at the Natural History Museum and the Game and Wildlife Conservation Trust.

Sites were identified using the Forestry Commission management database. Sampling took place at each site within 50m x 50m plots, selected as close as possible to the site centre. Vegetation structure and species composition was recorded to species in six, randomly located, 2 m^2 quadrats. In addition, the key components of the Condition Standards Monitoring target indicators (Table 1) were incorporated into the vegetation survey. Soil invertebrates were sampled from six randomly located 25 x 25 x 10 cm deep soil pits. Soil was hand sorted to remove invertebrates which were then preserved in ethanol and identified to species using a binocular microscope. Ground active invertebrates were sampled using pitfalls traps. Six large (500 ml) and six small (250 ml) plastic pitfall traps were set and left open for one week. Pitfall traps contained water and ethylene glycol (preservative) and a couple of drops of scentless detergent to break surface tension. Samples were subsequently preserved in 70% ethanol and identified to species. Invertebrates active in the aerial parts of the vegetation were sampled using five sweep net samples -the maximum number that fitted into the sampling area. Each sample comprised 25 sweeps taken on a random zigzag walk. Samples were initially frozen before being processed, preserved in 70% ethanol and identified primarily to family (due to the presence of many nymphs) and to species for selected groups. Grazing is unrestricted across the Open Forest but resulting variability in grazing pressure between sampling sites was minimized by replication over a large area.

Data preparation

CSM guidelines formed the basis from which to estimate the 'Heathland Condition' at each site. Data were averaged across quadrats within each site. Allocation of average data scores was used as a quantitative variable for analysis: for each positive target condition met (Table 1), one point was allocated, for each negative indicator a point was deducted. Total points provided the "Heathland Condition" estimate.

Table 1. The target indicators for Heathland Condition as outlined in the JNCC condition assessment: parameters that surveyors report against when assessing habitat condition. (http://data.jncc.gov.uk/data/cea45297-15af-46b7-8bf4-935d88b0a30a/CSM-LowlandHeathland-2009.pdf accessed 10/07/22)

Indicator	Target (% cover, or no. species assessed at each survey point)

POSITIVE INDICATORS	
% Cover:	
Bare ground	1-10%
Dwarf shrub[1]	25 – 90%
Dwarf shrub (to meet conservation objectives)	50-75%
Ulex	<25%
Dwarf shrub: no. of species	At least 2 species
Structure:	
Pioneer growth phase	10-40%
Building/mature	20- 80%
Degenerate	<30%
Dead	<10%
Composition:	
Graminoids[2]	>1 species
Forbs[3]	>1 desirable species
Lichen	Present

[1] Dwarf shrubs include: *Arctostaphylos uva-ursi; Calluna vulgaris; Empetrum nigrum; Erica ciliaris; E. cinerea; E. vagans; Genista anglica; G. pilosa; Ulex gallii, U. minor; Vaccinium myrtillis; V. vitis-idaea* (and hybrids).

[2] Graminoids include: *Agrostis* spp.; *Galium saxatile*; *Carex* spp.; *Danthonia decumbens; Deschampsia flexuosa; Festuca* spp. *Molinea caerulea*, *Nardus stricta; Trichophorum cespitosum.*

[3] Desirable forbs include: *Armeria maritime; Galium saxatile; Genista anglica; Hypochaeris radicata; Lotus corniculatus; Plantago lanceolata; Plantago maritime; Polygala serpyllifolia; Potentilla erecta; Rumes acetosella; Scilla verna; Serratula tinctoria; Thymus praecox; Viola riviniana.*

NEGATIVE INDICATORS	
Nardus stricta & *Deschampsia flexuosa*	<25%
Exotics[4]	<1%
Ragwort, nettles, thistles. Other undesirable herbaceous sp.[5]	<1%
Trees and scrub	<15%
Bracken	<10%

Vegetation data were grouped to represent the aspects of vegetation of interest to managers (i.e. Heathland Condition; amount of grass for grazing; bare-ground (for basking reptiles and some invertebrates) and cover of indicator species such as lichen. Variables used in analyses were: Heathland Condition (see above); vegetation height and % cover of:

bare ground; dwarf shrubs (together); heathers; gorse; graminoids (grasses, rushes, sedges); grass alone; sedges and rushes (with no grass); the three most frequently occurring grasses (bristle bent *Agrostis curtisii*. purple moor grass *Molinia caerulea*, heath grass *Danthonia decumbens*); bracken *Pteridium aquilinum*; moss; lichen.

Invertebrate data were grouped to represent aspects of biodiversity that are key indicators of good heathland management. Invertebrate variables were: the number of invertebrate food items of heathland specialist birds - Dartford warbler *Sylvia undata* (Araneae; Hemiptera; Coleoptera; Lepidoptera and Diptera) and Nightjar *Caprimulgus europaeus* (Hemiptera; Neuroptera; Coleoptera; Orthoptera; Lepidoptera; Hymenoptera and Diptera); 'Heathland specialists' both as a group, and separately, as follows: *Kleidocerys ericae*; *Micrelus ericae*: *Neliocarus sus*; *Ulopa reticulata*; *Ditropis pteridis; Chorthippus parallelus*; *Chorthippus*

[4] Exotics: *Rhododendron ponticum; Gaultheria shallon; Fallopa japonica.*

[5] Undesirable herbaceous species include: *Cirsium arvense, Digitalis purpurea, Epilobium* spp. (Exc. *E. palustre*), *Chamerion angustfolium, Juncus effuses, J. squarrosus*, *Ranunculus* spp., *Senecio* spp.

vagans; *Myrmeleotettix maculatus*, and two families of spiders: Linyphiidae and Lycosidae, which predominate in a well-structured canopy and open ground respectively. The abundance of beetles known to be responsive to management were also analysed (*Abax parallelepipedus, Agriotes obscurous, Carabus granulatus, Carabus problematicus, Chaetocnema concinna, Cicindela campestris, Drusilla canaliculata, Harpalus rufipes, Nebria salina, Onthophagus similis, Sitona lineatu*s) (McFerran et al., 1994, Hanson et al., 2016). The number of invertebrate food items rather than their biomass was chosen because previous investigations have shown that both metrics provide corresponding results when evaluating habitats (Anon 2010; Smith et al., 2020).

Data analysis

Data were tested to determine whether they satisfied the assumption of homoscedasticity by inspection of residuals vs fitted values and QQ plots, where this was not the case percentage data were arcsine transformed and count data were $\log_{10}$ (X+1) and tested again. All data presented here satisfy the assumptions of the test.

ANOVA models assessed the impact of management on vegetation and invertebrates (GENSTAT v15.1) testing for the effect of management type, age of plot and controlling for the block effect. Because insufficient replication of baled areas was available, we split the analyses to minimise use of unbalanced analytical designs. Primary analyses were conducted on the full chronosequence of 0–20 years, comparing burned and swiped sites. Secondary analyses included all three treatments (burned, baled, swiped) excluding 20-year plots.

In order to determine potential for management outcomes to affect heathland birds, we explored the relationship between vegetation components and the food items available to Dartford warblers and Nightjars. First, a partial correlation matrix was created using the PARTIALCORRELATIONS procedure in GENSTAT (v15.1) which calculates a symmetric matrix of partial correlations from a set of variates. The matrix contains the correlation between each pair of variates after adjusting for all the other variates in the set. We calculated correlations between each pair of: percentage cover of graminoids (which included grasses, sedges and rushes), grass, *Ulex*, heather, bare ground and vegetation height). The resulting correlation coefficient of 0.97 between grass and graminoids indicated that the graminoid group was dominated by grasses, therefore 'graminoids' was excluded from analysis. Two general linear models were then run, with cover of grass, *Ulex*, heather, bare ground and vegetation height as predictive parameters and Dartford warbler and Nightjar food groups as a response variable (in two separate analyses).

Species assemblages

In order to understand how treatments affected the species assemblage of communities arising, and how this changed across years, we used Canonical Correspondence Analysis (CCA) in the R package V*egan*, a multivariate method that examines patterns of species occurrences across samples and relates them to measured explanatory variables. This allows us to understand if the balance of species abundances, as well as the species identity, varies according to the variables of interest. In this case, the explanatory variables were: (1) treatment (burned, swiped and baled); (2) age of each plot. The three blocks were used as co-variables and their effects partialled out before analyses of treatment effects.

Vegetation quadrats within plots were treated as split plots within the whole plots, so as not to overestimate the P-values of the analyses. Invertebrate samples were pooled within plots for the soil pit, small and large pitfall, and sweep net data.

The association of treatments and species present in the plots was tested using a permutation test for each explanatory variable using indicator species analysis (R package, *indval*). These tests showed which variables had a significant association with particular species in the plots. This approach has long been identified as useful for identifying indicator organisms in the monitoring of protected areas (Kremen, 1992). Analyses were carried out in R version R.2.14.0, using the packages *vegan* (CCA) and *indicspecies* (indicator species analysis).

Data were collected from 105 sites, resulting in 642 quadrats of vegetation data, 1284 pitfall traps, 535 sweep net samples and 642 soil pits.

Results

The ecological impact of prescribed burning

Heathland Condition

Prescribed burning created heathland sites that scored well for Heathland Condition, scoring higher than swiped sites. We found an interaction between the management technique used and time elapsed since management event. Not only was Heathland Condition consistently higher on sites that were burnt, Heathland Condition continued to improve over time on sites that had been burnt, but on swiped sites Heathland Condition had begun to decline by the time sites had reached 20 years post-management (Table 2).

Table 2. Results of Analyses of Variance comparing two management techniques on Heathland Condition in the New Forest (prescribed burning and swiping), on a chronosequence of sites between 0-20 years since management event.

	Years since management (mean cover(%))						
Management	***0***	***1***	***6***	***10***	***20***	**F**	***p***
Burn	8.5	9.3	10.2	10.5	10.6	2.6	0.043
Swipe	9.2	8.4	8.6	10.0	9.4		

Overall, baled sites were intermediate between burning and swiping, however Heathland Condition was good on baled sites and at 12 years, the condition of baled sites was comparable to burnt sites (mean score 10.2).

Vegetation

Comparing burnt vs swiped sites (Table 3), the following covered a significantly higher percentage of burnt sites when compared with swiped sites: bare ground (11% vs 8.5%), heather cover (32.5% vs 19.3%), the aggregated group of dwarf shrubs (considered a strong indicator of Heathland Condition) (39.8% vs 24.9%,), purple moor grass *Molinia caerulea* (19.2% vs 10.1%) and moss cover (5% vs 2.8%).

Burnt sites supported a lower percentage cover of: Bracken *Pteridium aquilinum* (3.5% vs 12.9%,), heath grass *Danthonia decumbens* (1.7% vs 3.1%), sedges & rushes (2.1% vs 4.6%) and broadleaved plants (2.9% vs 11.9%).

Table 3. Results of Analyses of Variance comparing two management techniques in the New Forest (prescribed burning and swiping), on aspects of vegetation cover.

	Management technique (mean cover (%))			
	Burn	**Swipe**	**F**	***p***
Bare Ground	11	8.5	3.91	0.052
Dwarf shrubs	39.8	24.9	20.98	<0.001
Heathers	32.5	19.3	17.36	<0.001
Bracken *Pteridium aquilinum*	3.5	12.9	8.63	0.004
Sedges and rushes	*2.1*	*4.6*	8.62	0.004
Heath grass *Danthonia decumbens*	1.7	7.7	7.77	0.007
Purple moor grass *Molinia caerulea*	*19.2*	*10.1*	19.59	<0.001
Broad-leaved plant cover	*2.9*	*11.9*	26.7	<0.001
Moss	*5*	*2.8*	10.2	0.002

Variables unaffected by management included vegetation height and percentage cover of: Bristle bent *Agrostis curtisii* (widespread over all sites)); grasses; gorse and lichen (see S2).

Dwarf shrub cover, heather and lichen all increased over time, although by 20 years after management there were signs of these decreasing; bare ground decreased over time (Table 4). No other variables responded to time since management significantly (S2).

Table 4. Results of Analyses of Variance comparing vegetation cover assessed on a chronosequence of sites between 0-20 years since heathland management event.

	Years since management (mean cover(%))						
	0	***1***	***6***	***10***	***20***	**F**	***p***
Bare Ground	20.5	14.8	3.7	4.7	3.6	6.72	<0.001
Dwarf shrubs	12.8	15.8	22.7	42.9	38.1	11.53	<0.001
Heathers	12.8	15.6	22.5	42.8	38	8.67	<0.001
Lichen	0.39	0.17	0.23	3.64	0.75	3.14	0.019

Baled sites had a greater cover of dwarf shrubs including heathers (mean cover 45.9%) than either the burnt (39.8%) or swiped (24.9%) sites. Cover of heath grass, purple moor grass, sedges & rushes, forbs and moss on baled sites was also similar to that of the burnt sites. The only exception was bracken; mean cover was intermediate (6.1%) between burnt (3.5%) and swiped sites (12.9%).

Sixteen broadleaved plant species were found across all types of sites, of which heath milkwort, heath bedstraw, tormentil and sheep's sorrel were the most common. All are typical of mildly acidic heaths. Bramble was also widely distributed. Just seven species were exclusively recorded on burnt plots, including some of the typically wet heath species such as bog myrtle and oblong-leaved sundew. Round-leaved sundew was found on both burnt and swiped sites - which shared five additional species not occurring on baled sites: hawkweed; honeysuckle; lemon balm; common sorrel; field speedwell. Overall swiped sites were the most diverse with 39 species occurring exclusively, including many species typical of grassland or associated with waste ground. Only four species occurred exclusively on baled sites, while baled and swiped sites shared a further ten species. Full details in S1.

Invertebrates

Only the small heather weevil *Micrelus ericae* and *Cicindela campestris* (the green tiger beetle) were recorded in significantly higher numbers on burnt sites. *M. ericae* is a heather specialist and *C. campestris* is a characteristic heathland species (Table 5).

Table 5. Results of Analyses of Variance comparing two management techniques in the New Forest (prescribed burning and swiping), on invertebrate abundance.

	Management technique (mean number of individuals per sample)			
	Burn	Swipe	F	*p*
Dartford warbler food items	13.72	33.67	32.64	<0.001
Nihgtjar food items	13.93	36.37	20.26	<0.001
Meadow grasshopper *Chorthippus parallelus*	*0.03*	*0.20*	20.79	<0.001
Heath grasshopper *Chorthippus vagans*	*0.03*	*0.19*	11.65	<0.001
Bracken bug *Ditropis pteridis*	*0.02*	*0.17*	7.21	0.009
Small heather weevil *Micrelus ericae*	*0.20*	*0.05*	5.45	0.022
Ground beetle *Harpalus rufipes*	*0.04*	*0.25*	7.95	0.006
Green tiger beetle *Cicindela campestris*	*0.14*	*0.00*	5.87	0.018
Click beetle *Agriotes obscurous*	*0.00*	*0.20*	4.3	0.041

In general, insects were more abundant on swiped sites, including meadow grasshopper *Chorthippus parallelus,* the characteristic heathland species heath grasshopper *Chorthippus vagans* and *Ditropis pteridis* (a bracken specialist bug) (although numbers of all three were very low). Heath grasshoppers are restricted to southern England -mainly Dorset and E. Hampshire (https://nbnatlas.org/ accessed 12/07/2022).

Beetles associated with grasses were more abundant on swiped sites, including *Agriotes obscurus* and *Harpalus rufipes,* but most beetles did not respond to management and neither did the heathland specialist plant bugs *Kleidocerys ericae*, *Neliocarus sus* and *Ulopa reticulata* (see S2).

Although abundance of Heathland Specialists (as a group), money spiders, *M. ericae* and *U. reticulata* were rather low, all increased significantly as time elapsed after management. (Table 6).

Table 6. Results of Analyses of Variance comparing invertebrate abundance assessed on a chronosequence of sites between 0-20 years since heathland management event in the New Forest.

	Years since management (mean number of individuals per sample)						
	0	*1*	*6*	*10*	*20*	F	*p*
Heathland specialist invertebrates	0.28	0.88	0.72	1.45	1.63	5.6	<0.001
Dartford warbler food items	14.92	23.06	26.62	25.45	26.90	5.78	<0.001
Nihgtjar food items	15.64	25.41	28.63	26.84	27.64	47.83	<0.001
Money spiders: Linyphiidae	0.68	0.67	1.70	2.01	2.12	5.87	<0.001
Small heather weevil *Micrelus ericae*	*0.01*	*0.04*	0.10	0.25	1.60	2.98	0.024
Bug *Ulopa reticulata*	*0.04*	*0.01*	0.02	0.17	0.14	4.59	0.002

The invertebrate prey items of two heathland specialist birds, the Dartford warbler and the Nightjar, were found on all sites of each management type and in all years of the chronosequence. The abundances of invertebrates making up Dartford warbler and Nightjar food group were found to be significantly higher on sites managed by cutting than those managed by burning. They also increased with time as it elapsed after management (Tables 5 and 6).

The relationship between vegetation and invertebrate food items of Dartford warblers and Nightjars.

Invertebrate prey associated with grassy areas avoided bare ground. The general linear model confirmed that aspects of the vegetation composition at a site could be used to predict the abundance of Dartford warbler food items which was more abundant as grass cover increased (estimate 0.0037, s.e. 0.00165, t(81)=2.24 *p* =0.028) and less abundant as bare ground increased (estimate -0.00828, s.e. 0.00247, t(81)=-3.36 *p*=0.001). Similarly, the abundance of invertebrates eaten by Nightjars showed abundance increasing with grass cover (estimate 0.00535, s.e. 0.00194, t(81)=-3.68 *p*=0.007) and declining with increasing bare ground (estimate -0.01068, s.e. 0.0029, t(81)=2.75 *p*=<0.001).

Species assemblages

In all cases the management treatments significantly affected the species assemblages of both vegetation and invertebrates. While there was a consistent difference between burnt and swiped plots, the baled plots tended to have a more variable response to management revealed by different sampling method (see Table 2). For taxa collected in soil pit samples and vegetation samples, the baled sites were significantly different in composition from both burnt and swiped sites, but invertebrates collected from baled sites in small pitfalls and sweep nets were more similar to the burned sites than the swiped sites. Furthermore, invertebrates collected in large pitfall traps showed no difference between management (Table 2).

Table 7. Summary of results of Monte Carlo permutation tests (pseudo-F values in permutation tests) of treatments in Canonical Correspondence Analyses of community composition, comparing invertebrate species assemblages on burned, swiped and baled sites in the New Forest. Key – bl - baled, bn – burned, sw – swiped. P-values; * = 0.01 - 0.05, * <0.005. A significant response indicates that the community composition as a whole responded to either management or time since management. Abbreviations: pitfalls (S) = small pitfalls; pitfalls (L) = large pitfalls; sweeps = sweep net samples**

Burned v swiped:					
	soil pits	**pitfalls (S)**	**pitfalls (L)**	**sweeps**	**vegetation**
Management	5.1***	4.6 ***	4.3***	6.1***	5.3***
Age	0.7 ^{ns}	0.5^{ns}	0.8^{ns}	1.3 *	7.0***
All treatments:					
	soil pits	**pitfalls (S)**	**pitfalls (L)**	**sweeps**	**vegetation**
Management	bn ≠ bl ≠ sw	(bn = bl) ≠ sw	(bn≠ sw; bn=bl=sw)	(bn = bl) ≠ sw	bn ≠ bl ≠ sw
Age	1.1^{ns}	0.8^{ns}	0.5^{ns}	0.4^{ns}	6.1***

Time elapsed since management influenced species composition but revealed a different response across the sampling methods: above-ground (vegetation and sweep net samples) showed a significant association with time but below-ground or ground-level (pitfall trap) sampling did not (Table 2).

In all treatments, species which were most strongly associated with either burning or cutting were generally heathland specialists or grassland/arable specialists respectively (Table 8). In soil pits these were mostly earthworms (Table 8), while in the pitfall traps, they were predominantly ground beetles (Carabidae) (Table 8). Three of the beetle species found to be influential in the ordinations determined by CCA, and therefore important distinguishing species between the treatments, were of national conservation importance in the UK (Table 8) (*Bembidion bipunctatum, Amara equestris, Poecilius lepidus*). Two of them were in the burned treatment plots and one in the baled treatment plots. Unfortunately, most conservation-important species are too rare in the dataset to be informative in the ordinations.

Table 8: Invertebrate species from different sampling methods associated with management treatments. Nb = Notable b species (national scarce species found in between 31 and 100 hectads. A hectad is an ordnance survey square of one hectare).

Management	Sampling method	Species	Family	Typical habitat
Swiped	Soil pits	*Aporrectodea rosea*	Lumbricidae	grassland, woodland and arable land on basic soils
		Octolasion lacteum	Lumbricidae	wet grassland
		Aporrectodea caliginosa	Lumbricidae	grassland, woodland and arable land on basic soils
		Aporrectodea icterica	Lumbricidae	Wet soils, particularly grasslands
		Lumbricus rubellus	Lumbricidae	most habitats
		Allolobophora chlorotica	Lumbricidae	grassland, woodland and arable land, broadly neutral soils with high fertility.
		Pterostichus melanarius	Carabidae	non-basic grasslands and arable fields
		Byrrhus pilula	Byrrhidae	moss-feeder
		Nalassus laevioctostriatus	Tenebrionidae	In most habitats, feeds on cyanobacteria
		Armadillium vulgare	*Isopoda*	Often synanthropic
		Barypeithes araneiformis	*Curculionidae*	On young herbaceous plants; and trees
	Small pitfall	*Agriotes obscurous*	*Elateridae*	widely distributed and common, especially in agricultural habitats
		Chaetocnema concinna	*Chrysomelidae*	pollen-feeders on herbs and trees
		Chaetocnema hortensis	*Chrysomelidae*	widespread and common on wild and cultivated grasses

		Harpalus rufipes	*Carabidae*	dry, open situations, especially arable fields on sand and chalk
	Large pitfall	*Acalles ptinoides*	Curculionidae	in woods and in heathland
		Pterostichus madidus	Carabidae	very common in garden, woodland and dry grassland
		Ischnosoma splendidum	Staphylinidae	woodlands, especially pine plantations
		Amara tibialis	Carabidae	open areas of sandy grassland and heath
		Amara aenea	Carabidae	dry, open, sunny habitats
		Aleochara bipustulata	Staphylinidae	wide range of open habitats, especially arable land
Baled	Soil pits	***Bembidion bipunctatum***	***Carabidae***	**sand and gravel near running and still water (Nb)**
		Allolobophoridella eiseni	*Lumbricidae*	moorlands, bogs and woodlands on acid soils
Burned	Soil pits	*Notiophilus biguttaus*	*Carabidae*	All habitats, especially woodland
	Small pitfall	*Drusilla canaliculata*	*Staphylinidae*	all open areas
		Geostiba circellaris	*Staphylinidae*	most habitats
		Sitona lineata	*Curculionidae*	most habitats
		Carabus problematicus	*Carabidae*	long grassland, woodland, heaths
		Onthophagus similis	*Scarabaeidae*	horse or sheep dung on chalky or sandy soils
		Abax parallelepipedus	*Carabidae*	woods and open moorland
		Carabus granulatus	*Carabidae*	marshes and fens
		Cicindela campestris	*Carabidae*	open heaths and moors
		Nebria salina	*Carabidae*	unproductive habitats - heaths, sand dunes and upland grassland
		Amara equestris	***Carabidae***	**open, dry, sandy or calcareous habitats (Nb)**
		Cicindela campestris	*Carabidae*	open heaths and moors
		Dyschirius globosus	*Carabidae*	damp, bare or sparsely vegetated ground, often on peat

		Neliocarpus sus	Curculionidae	feeds on heather
		Carabus granulatus	*Carabidae*	marshes and fens
		Drusilla canaliculata	*Staphylinidae*	all open areas
		Abax parallelepipedus	*Carabidae*	woods and open moorland
		Poecilius lepidus	***Carabidae***	**dry, exposed, southern heaths (Nb)**

Discussion

Our work finds no evidence that burning is detrimental for the investigated components of biodiversity and that appropriate burning results in good Heathland Condition. Additionally, our study highlights that different management techniques result in different species assemblages, indicating that a mosaic of management treatments is likely to benefit overall biodiversity while suggesting that choice of management treatment is crucial in determining the balance of species.

Cutting by swiping does not replicate the effects of burning and therefore cannot be considered a substitute. Compared to burning, it encourages grassland species and as one component within a mixed management regime, it is beneficial through providing grazing, foraging for Dartford warblers and Nightjars as well as good habitat for invertebrate herbivorous species such as grasshoppers. However, too much grassland habitat lowers the condition of heathland. Prescribed burning encourages good quality heath: high dwarf shrub cover, low bracken cover, habitat for some heathland specialist invertebrates and, in the early years, open habitat for reptiles and ground active invertebrates. Moreover, where there are high densities of livestock, the benefits associated with grassland may be reduced, as heavy grazing negates many of the benefits for invertebrates, especially grasshoppers (Joubert et al., 2016).

Baling heather appeared to lead to an intermediate position, but our confidence is reduced by the low replication in the study. Furthermore, heather is baled with the aim of producing high quality material for restoration projects and paths around the forest - consequently the baled sites are selectively chosen for high heather cover and were probably in better habitat condition at the outset.

Currently 10% of the land that is managed annually in the New Forest is cut rather than burnt, and our work shows that while some cutting is beneficial for biodiversity, the impact of substantially increasing this is could be negative for biodiversity. However, the Common Standard Monitoring (CSM) – through relying purely on vegetation characteristics to indicate condition and ignoring invertebrates and birds - does not reveal the important resources that cut habitats provide for heathland species at higher trophic levels.

Management impact on Heathland Condition and vegetation.

Heathland Condition was strongly influenced by management practice. Prescribed burning delivered habitat more closely matching the criteria for good condition lowland heath according to CSM)assessment. This is in agreement with early studies that investigated short-term regeneration of heath (Sedláková and Chytrý, 1999). Burning encouraged dwarf shrubs, especially heathers, and also resulted in a marginally more open habitat. The CSM criteria indicate minimum 25% dwarf shrub cover as a target threshold. Burnt sites comfortably exceeded this (at 40%) whereas cut sites narrowly met it at 25%. However, neither burnt nor cut sites reached the 50-75% required to meet conservation objectives. Bracken dominates in poor Heathland Condition and is a problem on lowland heathland. Swiping increased bracken cover, which, on average, crossed the 10% threshold at which the CSM considers it negative, whereas on burnt sites cover was maintained at an average of 3.5%. Grass cover, as a whole, did not differ between the management types but species responded differently; burning encouraged purple moor grass and cutting encouraged heath grass, both characteristic species of heathland habitats. However while heath grass cover was low (<5% irrespective of management), purple moor grass approached an average of 20% on burnt sites, potentially due to the post burn release of nutrients (Shelswell *et al.*, 2011). Twenty percent is within the target guidelines. There is evidence that grazing could reduce this further and encourage greater ericoid cover (Newton *et al*., 2009). Appropriate grazing can also introduce additional vegetation structural diversity (Lake *et a*l., 2001, Tallowin *et al*., 2005), although grazing impact is determined by stocking rates, species, breed and periods of grazing (Rosa García *et al*., 2013). In this study free ranging cattle, horses, and deer had access to the areas throughout the year but their numbers were not recorded.

Swiping resulted in higher diversity and cover of broadleaved species including species usually associated with grassland and waste ground, not typical of heathland habitats and absent from the burnt sites. Overall, using vegetative indicators, the results suggest that, on balance, burning delivers better CSM Habitat Condition than vegetation swiping.

Management impact on invertebrates

Invertebrate species assemblage composition differed between management treatments and, reflecting the vegetation data, baled sites were intermediate between burnt and swiped sites, with a tendency to be more similar to burnt sites. When examined individually, above ground, characteristic heathland invertebrate species were largely unaffected by different management techniques, although where differences were found, it was the swiped sites that supported greater abundance and generally invertebrate abundance was positively correlated with grass cover. It is worth noting that heath grasshopper, rare in the UK and understudied everywhere (Haes and Harding, 1997) was more abundant on the swiped sites.

The below ground invertebrates reveal a potential early warning that the heathland areas are in danger of deteriorating. Firstly endogeic earthworms - horizontally burrowing species found only in areas with well-developed soil structure, such as pasture, arable land and neutral to base-rich woodlands - in the heathland plots suggests the presence of grassy patches that do not sustain good heathland. Previous work has suggested that grassy areas are likely to be grazed heavily resulting in enrichment by dung which further improves conditions for earthworms (Carpenter *et al.*, 2012). These processes are likely to encourage non-heathland species to grow which reflects what we observed in the swiped plots.

The second factor is the presence of species that rely on bare earth for thermoregulation; this includes numerous conservation-important, ground beetle species known to be characteristic of open areas (e.g. *Amara equestris, Cicindela campestris, Drusilla caniculatus, Nebria salina*, and *Poecilius lepidus*). These species are potentially excluded from areas with high grassland cover without bare patches. This is likely to be true of species in other invertebrate orders, such as Lycosidae, a hunting spider family which choose open patches and was only found on baled sites. In conclusion, while swiping is important in maintaining a mosaic with grassy areas, burning remains an important to ensure that grassy areas do not increase in heather dominated areas.

Management impact on birds

We could not assess the extent to which birds were directly benefited by managed habitats, as birds operate at a larger spatial scale than the managed plots. Instead, we inferred the value of the different management techniques by calculating the abundance of the different species eaten by two insectivorous heathland specialists: the diurnal Dartford warbler and the crepuscular Nightjar. We found that the swiped sites provided a more abundant food source than burnt areas, but both species nest on heathland (the Nightjar nesting on open ground (Langston *et al.*, 2007) and the Dartford warbler nesting in tall heather or gorse bushes, on which it is known to be dependent (Tubbs, 1963; van den Berg *et al.*, 2001), supporting the need for a mosaic of burnt and swiped patches.

Comparison of above and below ground response to management

Above ground and below ground community responses to management are similar, presumably because all the treatments impose severe environmental perturbations on the plots. In contrast, responses to time since management differ considerably. Below ground organisms (from soil pits and pitfall traps) showed no significant compositional changes across the years, while the above ground (vegetation and invertebrates captured in sweep nets) show a clear successional change. This is likely due to the different factors influencing the species found in each 'strata'. The soil is a more stable environment only changing very slowly and the soil-inhabiting species are most affected by soil type, organic matter content, soil pH, moisture and temperature and much less affected by the vegetation above them (Burton et al., 2022). The beetles spend their larval stages in the soil and so soil conditions affect the numbers emerging. However, they may then undergo some redistribution influenced by above ground factors. Most of the invertebrates collected at or below ground were decomposers or predators of decomposers, with few herbivores thus explaining the low differences between treatments. In contrast, most sweep net species were herbivores or predators of herbivores -many with narrow food plant ranges. These species were strongly affected by vegetation change.

These differences should be considered when assessing the conservation impact of changes in management policy because they may affect species of conservation concern directly or indirectly by impacting on their food supplies (as may occur with the Dartford warbler). Management may also influence ecosystem functioning as indicated by the presence of endogeic earthworms in some of the heathland plots which may suggest more long-term changes are occurring.

Our results suggest that the current 20 year management cycle in the New forest is appropriate. While Heathland Condition on burned sites was still good at 20 years, it had begun to decline on sites that were cut. The community assemblage results also suggest that the vegetation community as a whole shifts over time. The cover of ericaceous species (which are the dominant species on heathland) was declining 20 years after management (although this did not affect the above ground invertebrates which continued to increase in abundance). While our results are in agreement with the current rotation cycle, further work looking at longer time-frames would be useful. The size of management patches (from between <1 – approximately 10 ha) was driven largely by pragmatic decisions in the New Forest (often proximity to local infrastructure and buildings). Although patch size was not investigated, given the good condition we observed on plots of all sizes, we would suggest that areas of up to 10 ha are acceptable and are likely to be rapidly recolonised by moderately mobile species. The impact of patch size is worth further investigation.

Conclusion

Extending the sampling beyond the criteria in Common Standards Monitoring (CSM) yielded important information CSM alone would not have revealed; the habitat created by swiping supports more abundant invertebrate life than that created by burning. Including some swiping in the rotation can result in a boost for invertebrates that are important in heathland specialist bird diet. However, burning remained the most effective management to mitigate declining Heathland Condition, and as such burning should continue to be encouraged across substantial areas in lowland heath. Nevertheless, our evidence indicates a more complicated story that than suggested by the binary choices presented in the heathland burning debate. Biodiversity is encouraged by a mosaic of different management techniques and more mobile species are likely to exploit the resources provided by each.

Author contributions

BMS, DC and PE conceived and managed the project and wrote and edited the paper; BMS and PE carried out statistical analyses; DC produced maps; JH advised on study design and sampling and edited the paper; FA carried out the study on nightjars and edited the paper; AGH wrote sections and edited the paper.

At all stages of research design and delivery key stakeholders of were consulted including: the National Park Authority (established 2005), the Forestry Commission (managing crown lands within the Forest), the Verderers (administering the New Forest's agricultural commoning practices); the Commoners Defence Association (representing Commoners' grazing interests); Natural England (the UK government's adviser for the natural environment in England); National Trust (own and manage adjoining heaths).

Data accessibility

Meta data is available at datadryad.org

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