Developing an integrated land management strategy for the restoration of moorland vegetation on *Molinia caerulea*-dominated vegetation for conservation purposes in upland Britain

A.L. Milligan*, P.D. Putwain, E.S. Cox, J. Ghorbani, M.G. Le Duc, R.H. Marrs*

*Present address: Scottish Environment Protection Agency
Rivers House
Irongray Road
Dumfries, DG2 0JE, UK

*Corresponding author at: Applied Vegetation Dynamics Laboratory, School of Biological Sciences, University of Liverpool, Liverpool L69 3GS, UK. Tel +44-151-794-4752; fax: +44-151-794-4940 E-mail address calluna@liv.ac.uk (R.H.Marrs)

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Abstract

*Molinia* encroachment is considered a major threat to moorland and heathland conservation in Europe, and there is a need to develop management strategies to control *Molinia* and restore *Calluna* moorland. Here we combined weed control and restoration treatments into an Integrated Land Management Strategy to provide a more sympathetic approach than previous prescriptions. We applied the following treatments in factorial combination to a *Molinia*-dominated moorland in the Yorkshire Dales: grazing (ESA prescription level versus no grazing), cutting (0, 1, 2 & 3 cuts), ± application of a graminicide and ±*Calluna* brash addition. The response of the vegetation was assessed for four years. These data were analyzed using a combination of univariate and multivariate analysis of variance based on constrained ordinations but combined with bivariate standard deviational ellipses. This combined approach was extremely useful in identifying trends in this complex dataset.

The only treatment that had consistent effects in the univariate analysis of variance was cutting, where there was increased bare ground, reduced vegetation height, increased species diversity and reduced *Molinia* cover. Cutting three times had the greatest effect, maintaining a reduced *Molinia* cover over four years. The multivariate analysis showed that there were important community level interactions. Grazing generally produced vegetation which had a greater moorland species complement. Where grazing was restricted the vegetation had a greater component of *Molinia* and other acid grassland species. The most effective treatment was the grazed plots, cut thrice, which maintained a low *Molinia* cover for longest and had less variation in moorland species in the fourth year. Graminicide and brash application had marginal effects on species composition, but the best plots were those given herbicide alone, or in combination with brash addition.

These results contrast with other studies, where non-selective herbicide treatment and *Calluna* addition were required to obtain *Molinia* control and *Calluna* regeneration. However, great variation has been found between sites, and managers should be prepared to tailor Integrated Land Management Strategies for their own site. This is likely to require a knowledge of the initial floristic composition, seed banks and experimentation.

*Key-words: Calluna vulgaris*, conservation, cutting, graminicide, grazing, herbicide, multivariate analysis of variance, seed addition, vegetation management
1. Introduction

British heather moorlands are internationally significant ecosystems, protected under the EC Habitat and Species Directive (92/43/EEC) and the subject of Biodiversity Action Plans (Anon, 1985a,b). Despite this, the quality of remaining moorland is under threat from a wide variety of factors, with only 14% of moorland in England assessed as “in favourable condition” (English Nature, 2001). One of the perceived threats to upland moors is the increase in grasses, especially Molinia caerulea, at the expense of dwarf shrub heath species like Calluna vulgaris, which are important components of these ecosystems from a conservation viewpoint. Here nomenclature follows Stace (1997) for higher plants and Corley & Hill (1981) for bryophytes, but following common practice Molinia caerulea and Calluna vulgaris are referred to by generic names. Increases in Molinia have also been found elsewhere in Europe, for example in Holland large areas of Dutch heathlands have been colonized by Molinia, which replaces heath vegetation (Diemont, & Heil, 1984; Heil & Diemont, 1983). These observed shifts in vegetation composition from Calluna to Molinia have been variously attributed to inappropriate burning and/or grazing regimes (Grant et al., 1963; Grant & Maxwell, 1988; Miller et al., 1984) and increased atmospheric nitrogen and sulphur deposition, especially in Holland (Hogg et al., 1995; Lee et al., 1992; Diemont, & Heil, 1984; Heil & Diemont, 1983; Roem, Klees & Berendse, 2002). Irrespective of the cause of these changes, there is a need to reduce the cover of Molinia and restore the characteristic dwarf shrub flora (Marrs et al., in press).

In the England and Wales, the funding mechanism for such moorland restoration work is currently being implemented through grant payment under Agri-environment schemes, eg Environmentally Sensitive Areas (ESA) or Countryside Stewardship (CSS) Schemes (MAFF, 1993, 1996). In such schemes, the policy objectives are to reduce Molinia cover and restore the dwarf shrub component of the moorland (Bardgett et al., 1995). However, until recently there has been very limited information available on how to achieve this, and there is still a need to develop cost-effective techniques for achieving these objectives. Recently a multi-site study tested factorial combinations of burning, grazing, glyphosate application and seed amendment in both Molinia-dominated and mixed Molinia/Calluna vegetation and showed that it was difficult to derive specific management prescriptions that worked in three regions in England (Todd et al., 2000; Marrs et al., in press). Only one consistent result was found: Molinia cover was always reduced by the application of the non-selective herbicide glyphosate. The other treatments either showed site-specific effects, or any impact was found on only one sampling occasion. Moreover, on Molinia-dominated sites (‘White’ moors; Thomas, 1951) litter removal in combination with seed addition was needed to enhance Calluna seedling colonization.

The success of glyphosate was important because at present it is the only herbicide approved for grass control on open upland moorland (MAFF no. 06941; PSD/HSE, 1988). However, there are a number of selective herbicides (graminicides), which should only control grasses, that have been identified as being potentially useful for Molinia control (Milligan et al., 1999 2003a,b). Graminicides reduced Molinia for at least a period of two years and did not affect Calluna. However, extensive, repeated use of selective herbicides on a large scale could be expensive and may lead to the build up of harmful residues (Clay & Stephens, 1991). As most moorland restoration work carried out under Agri-Environment Schemes is done partly for environmental or conservation reasons, the wide-scale use of
non-selective herbicides, or even selective ones, may not find favour.

Grazing also plays an important role, and this is bound up with the need to provide grazing livestock with the maximum possible level of nutrition throughout the year (Maxwell et al. 1986). To achieve this there must be an adequate mixture of Molinia and Calluna (Maxwell et al. 1986). Molinia is a highly digestible species but as it has a relatively short growing season (late April to late August) it only provides summer feed, and Calluna, although having a lower nutritional quality provides winter food (Grant & Maxwell 1988). Molinia is a highly digestible species but as it has a relatively short growing season (late April to late August) it only provides summer feed, and Calluna, although having a lower nutritional quality, provides winter food (Grant & Maxwell 1988). Summer grazing has been demonstrated to keep Molinia in check (Hulme et al., 2002). Thus, any management prescription should not attempt the total eradication of Molinia, but achieve a reduction in its dominance and an increase in the dwarf shrub component of the vegetation, especially Calluna. Moreover, the final mosaic produced will produce ecosystems with complex interaction between vegetation communities and livestock utilization (Palmer & Hester, 2000).

An alternative would be to include a disturbance treatment such as cutting into the management strategy. Cutting has the advantage of acting as both a control method, reducing the target Molinia, and a physical disturbance treatment, which has been shown to enhance dwarf shrub colonisation during Molinia control (Todd et al., 2000), presumably through exposure of bare soil and hence creation of regeneration niches (Cloy, 1984; Bakker, 1989). Cutting has long been recognised as an effective method for conservation management of plant communities (Bakker, 1989; Worrall & Palmer, 1988; Wells & Cox, 1993), and for controlling invasive perennial species, e.g., Betula spp. (Marrs, 1984, 1985; 1987) and Pteridium aquilinum (Lowday & Marrs, 1992; Marrs et al., 1998; Le Duc et al., 2003). These species, like Molinia, have a considerable potential for rapid recovery after initial good control (Morton, 1977). Cutting Molinia in wet grasslands and lowland heathlands can be effective in reducing its abundance, depending on the severity, timing and frequency (Schoppguth et al., 1994; Hogg et al., 1995; Moen, 1995; Grant et al., 1996). Nevertheless the effects of cutting Molinia in upland British moorland on a large scale has not been examined experimentally. Moreover no attempt has been made to examine the use of cutting in conjunction with other techniques for reducing Molinia and restoring heathland vegetation under experimental conditions.

Here we tested the effects of: (a) grazing - sheep and rabbit grazing versus no grazing, (b) up to three repeat cuts in the first season; (c) application of selective herbicides; and (d) addition of Calluna propagules in the form of brash for the control of Molinia and subsequent development of moorland vegetation over a four year period. The aim was to develop an Integrated Land Management Strategy (ILMS) combining an integrated weed control (IWC) and a restoration strategy (Mulder & Doll, 1993; Buhler 2002; Zoschke, 1994). The IWC approach combines more than one weed control technique to control the abundance of a species or species group, and usually this involves both mechanical and herbicide methods (Popay & Field, 1996). However, some of the treatments applied here have a dual function, eg cutting and grazing also contribute to restoration.
2. Methods
The experiment was carried out at Ramsgill Bents, North Yorkshire (National grid reference SE41054715; Longitude 1° 50’ 27’’ W; Latitude 54° 8’ 27’’ N), a *Molinia*-dominated, or ‘White’ moorland.

2.1. Experimental design

The four factors to be tested (grazing pressure, cutting frequency, herbicide application and *Calluna* propagule addition) were applied in a randomised block (*n* = 2) split-split plot design. Within each block (50 m x 60 m), two grazing treatments were applied as main-plot treatments; the current moorland ESA-prescription sheep grazing pressure (*ca.* 1.8 ewes ha\(^{-1}\) yr\(^{-1}\)), which is uncontrolled free-range grazing plus an effect from an unknown rabbit density versus reduced grazing, where sheep and rabbit grazing was prevented by fenced exclosures.

Within each main-plot (48 m x 24m), four cutting treatments were applied as sub-plot treatments: (a) uncut, (b) cut once (December 1995), (c) cut twice (December 1995 & June 1996), and (d) cut thrice (December 1995, June 1996 & July 1996). Within each sub-plot (24m x 6m), further treatment combinations of selective herbicide application (quizalofop-ethyl) and/or *Calluna* brash addition were added in factorial combination at the sub-sub-plot level. Each of the 32 sub-sub-plots in each block measured 5 m x 10 m. All treatment combinations were allocated to plots randomly.

2.2. Field procedures

Cutting was carried out using a tractor-mounted, drum flail-mower. As the intention here was to cut as close to the ground as possible, the height of the cutter was reduced between cuts as vegetation height was progressively reduced. Cutting height was approximately 25 cm from ground surface in cut 1, reducing to 10 cm in cut 2, and 5 cm in cut 3. Because of the undulating ground, stretches of mineral soil were exposed on elevated ground at the third cut. Litter was not removed from the site and did not blow on to uncut plots. The exclosures were erected in July 1996, immediately after the last cut was applied.

The grass-selective herbicide, quizalofop-ethyl (trade name Pilot, AgrEvo Ltd, 0.5 kg a.i. litre\(^{-1}\)) was selected for use after preliminary laboratory trials showed it had potential to control *Molinia* whilst leaving *Calluna* relatively unharmed (Milligan et al. 1999, 2003a). It was first applied to the herbicide-treated plots at 0.25 kg ai ha\(^{-1}\) (0.5 litre ha\(^{-1}\)) in July 1996 but after four weeks little effect was noticed. A second dose was, therefore, applied in August 1997 at 0.50 kg ai ha\(^{-1}\) (1.0 litre ha\(^{-1}\)). Both herbicide additions were applied using a knapsack sprayer with an application volume of 170 litres ha\(^{-1}\) (flat fan nozzle, 2 bar pressure).

*Calluna* brash, cut and baled at Helmsley, North Yorkshire (National grid reference SE 461583; Longitude 1° 3’ 10’’ W; Latitude 54° 14’ 21’’ N), during November-December 1996 was spread in the brash addition treatments in January 1997. Two bales were added to each 5 x 10 m plot. Thirty bales were selected randomly and taken to the laboratory and weighed (mean ± SE; 19.92 ± 0.88kg). A (*ca.* 100g) were taken from each of the thirty bales and the total number of capsules counted (2930 ± 29.7 capsules per sample). Within each sub-sample 30 capsules were chosen randomly and the number of viable seeds counted (4.36 ± 0.64 seeds per capsule). These data were used to estimate the amount of...
viable seed applied to each plot (510,000 per plot, 10,200 seeds m$^{-2}$).

2.3. Assessment procedures

Species cover was assessed visually in three permanent 1 m$^2$ quadrats within each sub-sub plot at the following times (a) June 1996 (cut 1 had been applied), (b) July 1996 (cuts 1 & 2 applied), (c) August 1996 (all cuts applied & fence erected) (d) June 1997, (e) August 1997, (f) August 1998 and August 1999. A series of vegetation physiognomic variables were also recorded at each quadrat: cover of bare ground, vegetation height and litter depth. Total species number and the Shannon-Weiner Diversity index were computed (Krebs, 1972). From August 1997, both Calluna seedling density and litter depth were recorded. Each 1 m$^2$ quadrat was sub-divided into 100 sub-sections to allow accurate assessment. The mean values of the three sub-quadrats were computed to provide a sub-sub-plot mean.

2.4. Statistical analysis

Analysis of variance was used to assess treatment effects on the cover of the major species and the physiognomic variables. A randomised block split-split plot model was used with treatments included as they were applied, with repeated measures where appropriate. Data were transformed (% = arcsin($\sqrt{x/100}$); counts = $\sqrt{x}$) and analyzed using PROC GLM (SAS, 1985) with treatment effects tested using the appropriate error term. Only significant differences (P < 0.05) are presented and discussed here; the results presented are of transformed means ± standard errors, but a back-transformation is provided for ease of interpretation.

Multivariate analyses (CANOCO for WINDOWS, ter Braak & Šmilauer, 1998) were also used to describe changes in the entire community composition using data from the August samples. Initially, a Detrended Correspondence Analysis was used to measure gradient lengths. The gradient lengths were 2.8 and 2.5 without and with the downweighting option for rare species, accordingly linear models (Redundancy Analysis -RDA) were used thereafter (ter Braak & Šmilauer, 1998). All subsequent analyses used the downweighting option.

Multivariate analysis of variance was then performed using the constrained ordination method, again using CANOCO for Windows (ter Braak & Šmilauer, 1998). With this approach, the significance of each factor and interaction was determined using separate runs of RDA. In each run the factors and their interactions were included as environmental variables, with experimental blocks included as covariables. Significance was assessed using restricted Monte Carlo permutation tests with 499 permutations. The model used was a split-split-split-split plot design with grazing at the top level, followed by cutting, herbicide and brash addition, and time.

Thereafter, the dispersion of the treatment plots in the species ordination space was examined using bivariate standard-deviational (SD) ellipses for axes 1 and 2. The algorithm used for this purpose was ELLIPSE.SAS, given by Ricklefs and Nealen (1998), implemented in EXCEL (Le Duc et al., in press). The ellipse parameters (size, shape, orientation, Le Duc et al., in press) were inspected but provided little additional information to that provided in the biplots, thus only biplots are presented here.
3. Results

At the start of the experiment, the most common species was *Molinia*, followed by *D. flexuosa*. There were lower amounts (0.5-20 %) of *Festuca ovina, Anthoxanthum odoratum, Galium saxatile, Juncus squarrosus, Vaccinium myrtillus*, and very small amounts (0.5-5%) of *Calluna* and *Erica tetralix*.

3.1. Effects of experimental treatment on individual variables

The significant results from the analysis of variance are summarised (Table 1) but gave limited information partly as a result of the variability in the cover of species at low abundance. The most consistent results were obtained for those variables that were available for measurement in every quadrat (physiognomy and *Molinia* cover). For other variables the results were patchy and significance was most evident when all of the treatments had just been applied, and for the species diversity variables after four years.

3.1.1. Physiognomy

The cover of bare ground was measured only in 1996 when the cutting treatments were applied as there was very little bare ground after 1997 as a result of sward recovery (Table 2a). However, during 1996 cutting significantly increased the amount of bare ground. After 6 months there was no significant effect on bare ground as a result of the first cut applied in winter but after 7 months there was a significant increase in bare ground in the plots cut twice and this was maintained until the eight month. However, the main effect was the third cut, which significantly increased the amount of bare ground.

Cutting was also the major treatment to reduce vegetation height, and this was found at each sampling point throughout the period (Table 2b); the effect of time was also significant. The effects were more significant early in the study and there was some recovery through time (Table 2b). Cutting three times effected the greatest reduction in vegetation height, and a reduction was still found after 44 months, reducing height from 31 to 17cm; other cutting treatments were similar to untreated values within seven months (cut x1) and 19 months (cut 2).

The only other significant effects on vegetation height were found as a result of herbicide and brash treatments but only at 20 months, although there was also a significant interaction between each of these treatments and time. There were no further significant interactions. Vegetation height was reduced at that time immediately after herbicide spraying (unsprayed mean height = 19cm (untransformed mean), 4.344 ± 0.197 (transformed mean ± SE); sprayed = 15cm, 3.880 ± 0.244; *F*=5.30, *P*<0.01) and brash application (no brash= 15cm 3.860±0.2603; +brash = 11cm, 3.344 ± 0.175; *F*=5.30, *P*<0.01).

After 20 months the effects of treatment on both litter cover and depth were assessed. No significant effects were found for litter cover and only one significant treatment effect was found for litter depth. Here cutting three times reduced the litter depth significantly from 3.5 cm to < 0.3 cm (Table 2c).

3.1.2. Effects of treatment on species number and diversity

There were few significant treatment effects on either species number or Shannon-Weiner index. Significant differences were found only in 1999 for both grazing and cutting, no other treatments were significant (species number – grazing *F*=332, *P*< 0.05, cutting *F*=8.49, *P*<0.05; Shannon-Weiner -grazing *F*=235, *P*< 0.05, cutting *F*=15.33, *P*<0.01). Both measures were greater in the ungrazed
compared to the grazed plot (species number, ungrazed = 8.31 ± 0.43, grazed = 6.31 ± 0.39; Shannon-Weiner - ungrazed = 0.42 ± 0.03, grazed = 0.38 ± 0.03). In the cut plots both measures increased with increasing intensity of cutting, and in plots cut thrice were markedly greater than the others (species number – uncut = 6.19 ± 0.48, cut x1 = 6.50 ± 0.59, cut x2 = 6.88 ± 0.46, cut x3 = 9.69 ± 0.61; Shannon-Weiner - uncut = 0.32 ± 0.03, cut x1 = 0.36 ± 0.03, cut x2 = 0.36 ± 0.03, cut x3 = 0.56 ± 0.02).

3.1.3. Effects of treatment on Molinia cover

Significant effects of cutting were found on Molinia cover on four of the seven sampling dates (Table 2) and a significant time x cutting interaction (\( F = 54.22, P < 0.001 \)). Cutting once had very little impact compared to the uncut treatment, indeed 6 months after cutting there appeared to be a compensatory increase in Molinia cover in the cut once treatment (Fig. 1). Cutting three times gave the greatest reduction in Molinia cover with a significant effect found for three years after the cutting was applied. The double cut was intermediate with a reduction compared to the uncut and cut once treatments, but not as effective as the thrice cut. No other treatment either on its own or in interaction had a significant effect on Molinia cover.

3.1.4. Effects of treatment on Calluna

There were no significant treatment effects detected on Calluna cover but a marked spatial effect between blocks (Fig. 2a). Over the experiment as a whole there was a slight increase in Calluna cover through time from 0.5 % to 2.3 %.

Cutting, herbicide and grazing also had an effect on Calluna seedling density in at least one of the last three sampling periods (August 1997, 1998 and 1999). In 1997 herbicide application increased Calluna seedling density from 0.7 (0.832 ± 0.547) to 3.5 (1.826 ± 0.427) seedlings m\(^{-2}\), and in 1998 grazing reduced Calluna seedling density from 3.7 (1.918 ± 0.339) to 1.1 (1.184 ± 0.415) seedlings m\(^{-2}\).

There were significant effects between cutting treatments with cutting twice and thrice having a greater number of seedlings than the uncut and cut once treatments. The cut twice treatment had slightly greater seedling densities at the start and then a slight decline over the three years until they were identical to the uncut and cut once plots. The cut thrice treatment, however, had the greatest density in 1997, and there was a doubling of numbers in 1998 followed by a decline again in 1999 (Fig. 2b).

3.2. Community responses to treatment

The multivariate analysis of variance (Table 3) shows that of the main treatment effects only grazing and time were significant, but there were many significant interactions. As the highest order interaction (time x grazing x cutting x herbicide x brash) was significant, the species-plot biplot from this model was used for all subsequent investigations. This significance of this model was re-tested with 9,999 permutations as recommended by Legendre and Legendre (1998); it was highly significant (trace = 0.599, \( F = 1.9, P < 0.0001 \)).

The species ordination (Fig. 3) shows a gradient on axis 1 from Molinia domination (+ve end) to an acid grassland/moor (-ve end). Axis 2 represents a gradient from wet acid grassland/moorland dominated by Juncus squarrosus and Nardus stricta (+ve end) to a drier acid grassland dominated by Festuca ovina (-ve end). Calluna vulgaris and Deschampsia flexuosa appear in the upper left quadrant indicating a relatively dry moorland, and Erica tetralix and Vaccinium vitis-idaea occupy a similar
position in the upper right quadrant indicating wetter conditions.

Only a selection of the most interesting treatments and treatment combinations are presented and discussed here. The individual treatments (Fig. 4) show important differences. The trends through time (Fig. 4a) indicate a general change from *Molinia* domination (+ve end axis 1) towards the acid grass/moorland for three years then a slight reversal in the fourth year, perhaps indicating that *Molinia* is recovering. The shape of the ellipses indicate that there was a major increase in the species pool in the second year, followed by a reduction in years three and four, but in these years there was a change towards more moorland species (-ve increase on axis 1 and slight +ve increase axis 2). The effect of grazing (Fig. 4b) shows a clear separation with ungrazed plots located more or less below the origin and grazed plots above. This suggests that grazing promoted moorland development, whereas no grazing promoted acid grassland.

The effects of cutting, herbicide application and brash addition, although not significant are presented to illustrate their effect (Figs 4c,d,e). The general trend for cutting is a slight move upwards on the biplot towards moorland, the effect of herbicide application is a slight increase in the species pool with a bias towards moorland species, and the effect of brash addition is barely distinguishable. This latter result is not too surprising given that brash addition is only likely to affect one species (*Calluna vulgaris*), and this species takes many years to establish and contribute to species cover (Gimingham, 1992).

3.2.1. Interaction between Grazing and Time (Fig. 5)

The ungrazed plots showed ellipses located in the *Molinia* – acid grassland areas. On grazed plots however, there was a difference from the start (one month after the fences were erected) with an increase in cover of acid/moorland/moorland species; this trend increased over the four years with a slow but consistent positive increase on Axis 2.

3.2.2. Interaction between Cutting and Time (Fig. 6)

The three cutting treatments all showed more or less the same pattern of response, although there were subtle differences. All uncut plots moved from *Molinia* domination along Axis 1 towards acid grassland in years two and three and then moved back again. The reversal in year four differed between cutting treatments; as the number of cuts increased the area of the ellipse reduced and there was an increasing trend towards moorland. This is illustrated by the year four ellipses, which were centred across Axis one in the Uncut, Cutx1 and Cutx2 treatments, but was located in the *Calluna vulgaris* quadrant in the Cutx3 treatment.

3.2.3. Interaction between Grazing x Cutting (Fig. 7)

This analysis produced two distinct types of response, the first where there was a change through time with respect to the treatment combination but a reversal in the direction of the approximate start conditions in year four; this occurred in ungrazed treatments irrespective of cutting treatment, although the Cutx3 treatment produced the best effect in year four, with the most of the ellipse clearly over Axis 1 in the wet moor quadrant. The grazed cutting treatments show a general trend through time, increasing the size of the species pool in year two, especially in the Cutx2 and Cutx3 plots. In all grazed plots the ellipse in year four is located within the dry moor quadrant; as number of cuts increased from zero to two there is an increase in ellipse size within the dry moor quadrant. Where three cuts were applied the
size of the ellipse is much smaller but it is completely located within the dry moor quadrant.

3.2.4. Interaction between Grazing x Cutting x Herbicide x Brash Addition

For brevity, only the most successful treatment combination in achieving moorland vegetation (grazing & cut thrice, Fig. 7) is illustrated and discussed here. This treatment combination was examined to assess the effects of herbicide and brash addition alone and in combination (Fig. 8). All of the treatment combinations moved from the Molinia-dominated quadrant through to the moorland quadrant, although the trajectories differ. Herbicide application produced a much greater expansion of the species pool in the year after application compared to the unsprayed plots, but this effect declined in years three and four (Figs 8a,b). Moreover, the increase in species in year two was in the moorland species area. The effect of brash had the opposite effect, here the increase in the species pool occurred where no brash was added, presumably because brash addition prevented species invasion by smothering (Figs 8c,d). In the individual treatment combinations, whilst all treatments show a trajectory from Molinia to moorland, the size of the ellipses gave different patterns. Where no herbicide or brash was applied the species pools were very small and in year four was edging towards Nardus stricta. Where either brash or herbicide alone was applied, there were different trajectories but for each treatment there was an overlap between each year indicating relatively smooth transitions; the brash treatment was also edging towards Nardus stricta. However, where both brash and herbicide were applied, the transitions were not as smooth indicating a staccato-type change (Fig. 8h), even though the final vegetation was centred on Calluna. The treatments that appeared nearest the Calluna target were herbicide application alone and combined with brash addition.

4. Discussion

In order to restore Calluna and other dwarf shrub heath communities on Molinia-dominated moorland for conservation purposes, the Molinia abundance must be reduced (Weed Control Phase, Vermeer & Berendse, 1983; Marrs et al., in press), and the heathland species need to be restored (Restoration Phase, Todd et al., 2000; Marrs et al., in press). Effectively, this requires the development of an Integrated Land Management Strategy. The initial weed control phase should reduce the Molinia, if possible create gaps and suitable niches for the establishment of Calluna and associated moorland species, before the Molinia begins to re-establish from tussock fragments or seed (Sansen & Koedam, 1996). To assure restoration success, a ‘window’ must be created where the Molinia competition is reduced so that Calluna can begin to establish before Molinia recovers. This ‘window’ should be at least eighteen months long to ensure Calluna becomes established and competes effectively with encroaching or re-establishing Molinia. In recent experiments a single application of glyphosate produced a reduction in Molinia cover for six years (Marrs et al., in press). We accept that 18 months is only the start of the succession, and further work is needed to judge longer-term success.

During this period, Molinia has some short-term advantages. First it sets seed during its first season, whereas Calluna takes at least two years from initial seedling establishment to produce seeds in upland Britain (Miles, 1974), and second, Molinia can attain its maximum biomass faster than Calluna, even though Calluna can eventually attain a higher biomass (Aerts & van der Peijl, 1993). Where recruitment is from the seed bank, Calluna has an advantage because seed viability is longer (Granström
In order to develop the ILMS, we tested a range of treatments designed to control Molinia and enhance moorland species without the use of the non-selective glyphosate. The four treatments were: cutting at the start of the experiment at various frequencies; grazing versus no grazing, selective herbicide use and brash addition. The first three treatments were aimed mainly at reducing the Molinia cover, although cutting and grazing also had disturbance effects, and the last one was intended to increase Calluna restoration.

A major feature of this work was the combined use of (a) univariate and (b) multivariate analysis using constrained ordinations to test for significant differences coupled with the use of bivariate standard deviational ellipses to investigate treatment effects and their interactions. This combination has proved a powerful tool for teasing out important effects and comparing treatment trajectories. It is certainly more informative than methods used hitherto (Milligan et al., 2003; Marrs et al., in press).

4.1. Effects of treatments

Cutting had the greatest effect on Molinia, reducing it for up to four years, especially where three cuts were applied. Increasing the number of cuts produced more bare ground in the first year, which created more regeneration niches (sensu Grubb, 1977). Grazing had a lesser effect on Molinia, but the community analysis showed that it had a major effect on the development of moorland communities with a much more diverse vegetation developing on the plots grazed at the ESA prescription level than those ungrazed. The reduced sheep grazing and natural rabbit grazing pressure combined to produce plant communities that contained more moorland species; whereas where this grazing pressure prevented Molinia and other grasses such as Festuca ovina dominate. The grazed, cut treatments were the most effective in developing a moorland species composition and given the effect of the cut thrice treatment on Calluna seedlings this is the recommended treatment. Where grazing was applied there was an increasing trend towards moorland species, and where there was no grazing the trend was to a species-poor grassland.

The sheep grazing pressure at Ramsgill was calculated at 1.8 ewes ha$^{-1}$, an intermediate pressure in upland areas (ranges: 0.01 sheep ha$^{-1}$ for Pteridium aquilinum-dominated areas to 3.01 sheep ha$^{-1}$ on Nardus stricta/Vaccinium myrtillus-dominated areas; ADAS, 1997), but perhaps a little high with respect to sub-dominant heather moorland sites (0.57-1.18; ADAS, 1997). It is slightly greater than that suggested as possibly suitable for holding Molinia in check (0.6-1.4 sheep ha$^{-1}$, Hulme et al., 2002). The size of the rabbit population at Ramsgill is unknown but was substantially reduced in spring/summer 1996 (A. Swainston, per. comm.). This reduction may have helped to establish and maintain Calluna and other moorland species. However, the interactions are potentially complex. For example, field observations suggested that cutting prolonged the sheep-grazing season, with Molinia in plots cut twice and three times being preferentially grazed. Cutting may, therefore, have increased the attractiveness of Molinia and lengthened the grazing period; this may be important as sheep and other grazers are known not to graze Molinia toward the end of summer, preferring more palatable grasses and ericaceous species (Welch, 1984, 1986; Grant et al., 1985). The reasons are unclear but may result from more palatable regrowth or greater accessibility. However, it is possible that too high sheep pressures may damage Calluna growth and we suggest that in such circumstances it may be wise to graze the
remaining *Molinia* hard in spring and early summer to ensure continued reductions (Hulme et al., 2002). Left ungrazed, *Molinia* will increase in vigour and begin to encroach again (McAdam, 1992; Marrs et al., in press).

Application of selective herbicides was less effective; they reduced vegetation height on some sampling occasions but had no significant effect on *Molinia* cover. However, selective herbicides have been shown to be effective for *Molinia* under some circumstances (Milligan et al., 2003a). As there is some discrepancy in the value of using selective herbicides more wide scale studies are needed to assess their effects under a range of different application conditions.

The addition of brash reduced vegetation height in the year after application but there was no discernable effect on recruitment of *Calluna* seedlings. This implies that natural regeneration from the soil seed bank was adequate at this site, especially in the most disturbed plots, where the greatest densities were found. Here disturbance gave better results than brash addition. The *Calluna* seed bank at Rams Gill Bents was estimated to be 5000 seeds m$^{-2}$, although the variability was high (SE = 3870, n=10, Milligan 1998). We added a further 10,000 in the brash, but even this rate was much lower than the 40000 seeds m$^{-2}$ recommended for good *Calluna* establishment (Putwain & Rae 1988). Here *Calluna* seed was added in brash and there is a physical limit to the amount that can be added, because even with this amount there was some evidence of a smothering effect. Its is possible that better quality brash could be obtained with a greater number of viable seeds, or alternatively seed can be extracted from the brash and given smoke treatment to increase its viability. Smoke-treated seeds can be applied to moorland using hydraulic sprayers (GC Eyre pers. comm.).

4.2. Potential of Integrated Land Management Schemes

The combined application of techniques used in this study provided evidence of important interactions with respect to restoration for conservation purposes. Cutting (especially thrice) in combination with light grazing produced a vegetation trajectory towards a moorland species complement and cutting-thrice increased *Calluna* seedling densities. The most successful treatment combination thus provided a ‘window’ of *Molinia* reduction with associated increased bare ground and decreased litter depths and provided opportunities for developing a moorland vegetation with a mixed species complement. At this site the background natural *Calluna* regeneration was sufficient to allow *Calluna* to regenerate, especially in plots cut thrice, but on sites with a poorer *Calluna* seed bank, addition of seeds via brash or other techniques would be essential (Todd et al., 2000; Marrs et al., in press). However, whilst natural regeneration provided successful results, the community analysis indicated that herbicide addition alone or in combination with brash addition was closer to the *Calluna* position in the biplot and had a larger pool of moorland species.

One drawback to this study has been the short length of time needed for moorland development and clearly longer-term research is needed to assess the most appropriate and economic treatment in the longer-term. It may also be worthwhile considering the use of selective herbicides to reduce *Molinia* recovery during the moorland re-establishment phase (Milligan et al., 2003a,b; GC Eyre, pers. comm.). *Molinia* has been shown to re-establish and become dominant even after sustained disturbance (Sansen & Koedam, 1996). Therefore the continued management of established *Calluna* plants within the
Molinia mosaic is extremely important to ensure success. Sensitive grazing regimes, which reduce Molinia during the summer, yet protect Calluna plants from overgrazing in winter is strongly recommended.

A further drawback is that little is known of the effects of cutting on the fauna of these habitats. Cutting was timed to occur after the main breeding season for grouse (Lagopus lagopus) and curlew (Numenius arquata), which are common visitors to the study site. However the use of the cut sites by these species remains unknown. Further work is also necessary to clarify the effects of cutting on moorland invertebrates although increases and decreases will depend on the species present (Morris, 1981).

This study has shown that an Integrated Land Management Strategy using a combination of grazing and cutting here would be beneficial. Although costly initially, it would provide considerable conservation gains as the Calluna seedlings develop within a mosaic of other moorland species. Moreover, Marrs et al. (in press) have shown that there is a large variability in response of Molinia communities across the UK, and any attempt to develop site-specific ILMS may require further modifications, which will require additional experimentation.

Acknowledgments
We thank Mr J Currer-Briggs for access to Ramsgill Bents and much moral support, A Swainston, for practical help and historical information and DEFRA who funded this work.
References
of degraded *Calluna vulgaris* (L.) Hull-dominated wet heath by controlled sheep grazing. Biological Conservation 107, 351-363.


herbicides in the restoration of British moorland dominated by Molinia. Biological Conservation 109, 369-379.


Figure legends

Figure 1. Effects of cutting once, twice or thrice compared to uncut controls on *Molinia* cover at Ramsigill Bents over a four year period; mean values ± SE are presented of arcsin transformed data.

Key: uncut = ☐; cutx1 = ●; cutx2 = □; cutx3 = ■.

Figure 2. Effects of (a) spatial position (blocks) on *Calluna* cover (%), and (b) cutting once, twice or thrice compared to uncut controls on *Calluna* seedling densities (√x transformed) at Ramsigill Bents over a four year period; mean values ± SE are presented. Key: (a) Block 1 = ○; Block 2 = ●; (b) Uncut = ○; Cutx1 = ●; Cutx2 = □; Cutx3 = ■.

Figure 3. Species distribution in biplot produced from the RDA ordination testing all experimental treatments in combination (Table 3). Key to species codes: Ao = *Anthoxanthum odoratum*; Bs = *Bryophyte* spp; Cv = *Calluna vulgaris*; Df = *Deschampsia flexuosa*; Et = *Erica tetralix*; Fo = *Festuca ovina*; Gs = *Galium saxatile*; Js = *Juncus squarrosus*; Lc = *Luzula campestris*; Mc = *Molinia caerulea* (L = live; D = dead); Ns = *Nardus stricta*; Vv = *Vaccinium vitis-idaea*. Group A (grouped for clarity) include *Carex* spp, *Eriophorum vaginatum*, *Polytrichum commune*, *Racomitrium lanuginosum*, *Rhytidiadelphus squarrosus*, *Sphagnum* spp., *Trichophorum cespitosum*, *Vaccinium myrtillus*, *Vaccinium oxyccocus*.

Figure 4. Distribution of applied treatments in the biplot produced from the RDA testing all treatments in combination (Table 3) – these figures are directly comparable with the species distribution (Fig. 3). The effects of treatments on their own are displayed as bivariate standard-deviational (SD) ellipses for axes 1 and 2: (a) time (T), (b) grazing (G), (c) cutting (C), (d) herbicide application (H), (e) brash addition (B). Codes for G, H & B are 0 = no treatment; 1 = treatment; codes for cutting (C) are 0, 1, 2, 3 for zero, cutx1, cutx2 and cutx3; codes for time (T) are 1, 2, 3, 4 = 1996, 1997, 1998, 1999.

Figure 5. Distribution of grazing treatments through time in the biplot produced from the RDA testing all treatments in combination (Table 3) – these figures are comparable with the species distribution (Fig. 3). The effects of treatment combinations are displayed as bivariate standard-deviational (SD) ellipses for axes 1 and 2: (a) no grazing (G0), (b) grazing (G1). Codes for time (T) are 1, 2, 3, 4 = 1996, 1997, 1998, 1999.

Figure 6. Distribution of cutting treatments through time in the biplot produced from the RDA testing all treatments in combination (Table 3) – these figures are comparable with the species distribution (Fig. 3). The effects of treatment combinations are displayed as bivariate standard-deviational (SD) ellipses for axes 1 and 2: (a) Uncut (C0), (b) Cutx1 (C1), (c) Cutx2 (C2), (d) Cutx3 (C3). Codes for time (T) are 1, 2, 3, 4 = 1996, 1997, 1998, 1999.

Figure 7. Distribution of grazing x cutting treatments through time in the biplot produced from the RDA testing all treatments in combination (Table 3) – these figures are directly comparable with the species distribution (Fig. 3). The effects of treatment combinations are displayed as bivariate standard-deviational (SD) ellipses for axes 1 and 2: (a) no grazing + uncut (G0C0), (b) grazing + uncut (G1C0), (c) no grazing + Cutx1 (G0C1), (d) grazing + Cutx1 (G1C1), (e) no grazing + Cutx2 (G0C2), (f) grazing + Cutx2, (G1C2), (g) no grazing + Cutx3 (G0C3), (h) grazing + Cutx3
(G1C3). Codes for time (T) are 1, 2, 3, 4 = 1996, 1997, 1998, 1999.

Figure 8. Distribution of the herbicide and brash addition treatments and their interaction for the most successful grazing and cutting combination (ungrazed + cut three times) through time in the biplot produced from the RDA biplot testing all treatments in combination (Table 3) – these figures are directly comparable with the species distribution (Fig. 3). The treatments are shown as bivariate standard-deviational (SD) ellipses through time on axes 1 and 2: (a & b) herbicide treatments; (b & c) brash treatments, and (e,f,h,i) are the herbicide x brash treatment combinations. Key to time: Thick black 1996, Grey 1997, Light grey 1998, Thin black 1999.
Table 1
Significant responses (P<0.05) detected in univariate analyses of variance of the results of the moorland restoration experiment at Ramsgill Bents between 1996 and 1999: Key to treatments: C = Cutting, G = Grazing, H = herbicide, B = Brash, and a dash denoting that no measurement was made at that sampling occasion. *F*-values are presented with an indication of significance as follows: ns = not significant \( P > 0.05 \), * = \( P < 0.05 \), ** = \( P < 0.01 \), *** = \( P < 0.001 \).

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<th>Aug 96 (19)</th>
<th>Jul 97 (20)</th>
<th>Aug 97 (21)</th>
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</tbody>
</table>


### Table 2

The effects of cutting *Molinia*-dominated moorland on (a) cover of bare ground, (b) vegetation height, and (c) litter depth in a 44-month experiment at Ramsgill Bents. Data are transformed means ± SE, back transformed data are discussed in text.; significance levels are presented in Table 1.

(a) Bare ground (%; transformation = arcsin)

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<th>Cutting frequency</th>
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<th>Cut 2</th>
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<td>7</td>
<td></td>
<td>0.017±0.013</td>
<td>0.010±0.007</td>
<td>0.284±0.059</td>
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<td>8</td>
<td></td>
<td>0.016±0.010</td>
<td>0.032±0.014</td>
<td>0.094±0.042</td>
<td>0.402±0.092</td>
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(b) Height (cm; transformation = √x)

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<th>Cut 3</th>
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<td>4.259±0.067</td>
<td>3.905±0.091</td>
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<tr>
<td>7</td>
<td></td>
<td>5.189±0.127</td>
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<td>2.843±0.136</td>
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(c) Litter depth (cm; transformation = √x)

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<td>1.625±0.387</td>
<td>1.195±0.264</td>
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Table 3
Results of the multivariate analysis of variance using restricted permutation tests (499 permutations) of an experiment carried out to test the effects of management treatments (grazing versus no grazing, four levels of cutting, herbicide application and Calluna brash addition) to control Molinia and enhance moorland vegetation over a four year period at Ramsgill Bents. Codes are: $N_p =$ number of permutable units, Trace ($T_r$ - total sums of squares), $F$-ratio ($F$) and $P$-value ($P$).

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<tr>
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<td>Time x Cutting x Brash</td>
<td>9</td>
<td>256</td>
<td>0.279</td>
<td>3.1</td>
<td>0.002</td>
</tr>
<tr>
<td>Time x Cutting x Herbicide x Brash</td>
<td>9</td>
<td>256</td>
<td>0.364</td>
<td>2.0</td>
<td>0.002</td>
</tr>
<tr>
<td>Time x Grazing x Cutting x Herbicide x Brash</td>
<td>9</td>
<td>256</td>
<td>0.599</td>
<td>1.8</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Total 255
Figure 1.
(a) *Calluna* cover

![Graph showing *Calluna* cover over time](image)

(b) *Calluna* seedling density

![Graph showing *Calluna* seedling density over time](image)

Figure 2.
Figure 3.