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Department for Environment Food & Rural Affairs

Evidence Project Final Report

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Project identification

1. Defra Project code: BD5105
2. Project title: Implications of grazing regimes on vegetation, invertebrates and livestock performance and following heather restoration on degraded heathland (building on BD1228 and BD1243)
3. Contractor organisation(s): RSK ADAS Ltd
4. Total Defra project costs (agreed fixed price): £ 187,378
5. Project: start date .... 01 June 2012
   end date .... 31 March 2017

6. It is Defra's intention to publish this form.

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Extensively grazed heather moorlands in the uplands of the UK hold a unique assemblage of flora and fauna and are internationally important for their conservation value as well as providing a key resource for supporting rural economies and ecosystem services in upland Britain. However, heavy grazing from increased numbers of sheep in the 20th century caused a decline in dwarf shrub species including *Calluna vulgaris* (heather) and replacement by grasses with consequent effects on other biodiversity including invertebrates. Agri-environment schemes are intended to reverse these changes but better evidence is still needed on the effects of different grazing regimes on moorland habitats.

Under Defra project BD1228 the ecological and economic impacts of a range of sustainable grazing regimes were assessed. That project included system scale studies of sheep, cattle and mixed grazing regimes and plot-scale restoration experiments on degraded *Nardus stricta* (mat-grass) moorland at ADAS Pwllpeiran over a four-year period from 2003. The Pwllpeiran study was then extended until 2010 under project BD1243. From 2010 until the start of this phase of the study in 2012, the site was not grazed.

The objectives of this project were to

1. Reintroduce the grazing regimes on the 12 replicated treatment paddocks at Pwllpeiran in 2013 for a further 4 years.
2. Measure impacts on vegetation, invertebrates and livestock performance under the different grazing regimes following the 2-year period when grazing was excluded.
3. Introduce grazing to a subset of the heather restoration plots not grazed since the start of the experiment, and repeat heather assessments under the different grazing regimes.

The site comprised 72 ha of *N. stricta* moorland, which was formerly dwarf shrub heath but degraded by past heavy grazing. The area was divided into three blocks, each subdivided into four paddocks (12 paddocks in total). Four grazing treatments were applied from spring 2003 to autumn 2010, allocated randomly to paddocks and replicated over the three blocks. Treatments were low sheep (LS; 1.0 ewes per ha for 10 months per year + lamb from May to August), high sheep (HS; 1.5 ewes per ha for 10 months per year + lamb from May to August), cattle only (CO; 0.5 heifers per ha for 2 months in summer only) and mixed sheep plus cattle grazing (SC; low sheep + cattle). Welsh Mountain ewes and yearling Welsh Black heifers were used. From 2010 to 2012 none of the paddocks was grazed, and the grazing regimes were then reintroduced for a further four years from 2013 to 2016 under this contract. During this period, ewes were taken off the paddocks for tupping as previously, but were not returned over winter.

Smaller-scale heather restoration plot experiments were located within paddocks with three of the grazing treatments; HS, CO and SC. Plots were randomly assigned to one of three disturbance treatments (undisturbed, rotavation and trampling) in September 2002. All plots then had two sub-treatments applied to them in March 2003. *C. vulgaris* seed was broadcast at a rate of 0.8 g seed m-2 (26,000 seeds m^{-2}) on half of each plot. A no-grazing treatment was applied by fencing half of each plot perpendicular to the seeding treatment, to create a 2 x 2 factorial structure: (a) grazed, not seeded, (b) not grazed, not seeded, (c) not grazed, seeded and (d) grazed and seeded. From 2010 until 2012 all plots were ungrazed. In 2012 the fencing on half of the plots was then swapped over. Thus the half that was ungrazed from 2002-2012 became grazed and the half that was grazed became ungrazed.

Vegetation data were collected in 2012 and 2016 from a grid of 124 quadrats superimposed across the 12 paddocks. The effects of the grazing treatments were assessed on plant species composition and cover, the frequency and grazing on key species, and vegetation heights.

To sample invertebrates, pitfall traps were set for two sessions from July to August and September to October 2016 at a subset of vegetation quadrats. Individual adults and larvae (if present) were sorted into major taxonomic groups. Effects of grazing treatments, vegetation composition and vegetation height on the invertebrate groups were assessed.

Livestock data were recorded each year from 2013 to 2016. Liveweight and body condition scores were recorded for all heifers when turned onto and removed from the paddocks, and for ewes when turned out after lambing and at weaning in early September. Lambs were also weighed when turned out, at shearing in late June and at weaning.

In the heather restoration plots, shoots of *C. vulgaris* were measured for overall height, length of the current year's growth increment and browsing of the current or previous year's growth. Vegetation height and cover of plant species and bare ground were also recorded from the plots. Similarity of the plant community to a target community containing 50% *C. vulgaris* cover was also assessed.

During the period with no grazing, *N. stricta* frequency declined from 37.6% in 2010 to 30.8% in 2012 in the paddocks following a previous decline from 51.4% in 2003 to 36.8% in 2005. Mean vegetation height increased across all treatments during the period without grazing, but only by *c*. 2cm (from 15.5 cm in 2010 to 17.4 cm in 2012). Height variability also appeared to decline overall.

In 2012 after the period without grazing, the LS treatment had a significant effect on overall plant species composition across the paddocks, which was still apparent in 2016. LS still had a significant effect on the plant species composition. During 2012 to 2016, *C. vulgaris* frequency was greater in the CO treatment than in the other treatments. Frequency of *N. stricta* was very similar in 2012 and 2016, which followed the overall decline in frequency in previous years of the study. In 2016, overall grazing levels were very low on *C. vulgaris*, *Molinia caerulea* (purple moor-grass) and *N. stricta* but were higher on *Vaccinium myrtillus* (bilberry). Graminoids had the highest top cover values of all species groups in both 2012 and 2016, and increased significantly from *c.* 67% to *c.* 80% following the re-introduction of grazing. However, it was primarily the less palatable species that had increased. Conversely, covers of bryophytes, dwarf shrubs and forbs all decreased following re-introduction of grazing. Mean vegetation height across all paddocks declined by *c*. 4 cm during the 4-year period from 2012 to 2016. These changes were all consistent across the four grazing treatments.

Invertebrates were related to variation in plant species composition, all groups tending to be more associated with grassy rather than mire vegetation. In addition, most groups tended to be less associated with SC compared to all the other treatments, particularly Collembola (springtails), Diptera (fly) larvae and Hemiptera (true bugs). Chiloptera (centipedes and millipedes), Coleoptera (beetle) larvae and Mollusca (slugs and snails) tended to be associated with shorter rather than taller vegetation. Only Collembola were affected by grazing treatment, with most captured in LS and least in SC.

Cattle liveweights increased significantly during the period of grazing on the paddocks in three of the four years from 2013 to 2016. In 2013 only, the increase was slightly greater in the CO treatment than SC. Cattle condition scores also improved each year between turning out and removal from the paddocks. Liveweight gains varied from year to year but in 2013 were exceptionally good, following the two-year period when the site was not grazed.

Ewe liveweights also increased significantly in 2013 following the two-year period with no grazing, but declined in both 2014 and 2016. Lamb liveweight gains were less in HS than the other grazing treatments during 2013 and 2016. In 2013 only, gains in SC were greater than in the other treatments. Over the course of the extended study, lamb mean weaning weights varied from 23.8 kg in 2004 to 31.9 kg in 2007. There was no significant treatment effect on weaning weights of lambs in any of the four years from 2013 to 2016, nor had there been in the previous years of the extended study.

Introducing grazing into heather restoration plots which had not been grazed previously resulted in a decline in *C. vulgaris* cover, reduced growth increments and fewer shoots. *C. vulgaris* cover increased the most following the change from being grazed to ungrazed and declined when changed from ungrazed to grazed. There was greatest *C. vulgaris* cover, and it increased more, in the cattle only grazing treatment than in the sheep only or mixed grazing treatment, in disturbed than in undisturbed plots, and if seeded compared to unseeded. *C. vulgaris* was taller under cattle and mixed grazing than sheep grazing. After 14 years there was less *V. myrtillus* cover on plots currently grazed than those ungrazed. *N. stricta* cover was greater in the sheep grazed plots than the mixed grazed plots and in plots grazed during the initial 8 year period of grazing. Other plant species showed effects of either the most recent grazing regime or the initial period of grazing.

Between 2012 and 2016 sub-plots that had the grazing removed became more similar to the target community than did sub-plots that were previously ungrazed and then grazed. However, there were no significant differences between grazing treatments in their similarity to the target community. Under all grazing treatments plots that were originally disturbed and seeded were more similar to *C. vulgaris* dominated communities than grass dominated communities.

Conclusions:
1) There was evidence that competition among plant species was driving some of the longer-term changes in vegetation, and that this interacted with grazing.
2) Grazing *per se* had a greater effect on plant species composition at the paddock scale than the individual grazing treatments.
3) The cattle-only grazing regime was beneficial for *C. vulgaris* over the long-term.
4) Cessation and re-introduction of grazing also affected plant species cover in the shorter term.
5) Disturbance was also an important driver of the vegetation dynamics and might also have been the driver responsible for the relationship between grazing regimes and invertebrates.
6) Restoration of *C. vulgaris* was most successful with seed addition and disturbance at the outset, and with no subsequent grazing, or grazing under the cattle-only regime.
7) Manipulation of grazing alone will take many years to alter plant species composition.
8) It is likely that invertebrate communities will change in response to vegetation restoration in the long-term, as well as to more ephemeral effects of grazing management.
9) The two-year period without grazing appeared to have some short-term benefit in providing more, or better, forage for livestock in the following year.
10) There was little variation in livestock performance among the grazing regimes, apart from lamb performance in some years.
11) Management of moorland habitats for multiple objectives will require certain compromises to be made. Economic objectives will often preclude long-term cessation of grazing, and will also often require the inclusion of sheep in the grazing system. A rotational or pulsed grazing system similar to the one applied here could provide an acceptable compromise.
12) Pulsed grazing systems need to be tested on other moorland sites containing a range of habitat types to test their effectiveness more widely.
13) The most successful treatments for restoring *C. vulgaris* have been identified, but these need to be rolled out at larger spatial scales to test their application at the scale of a moorland grazing unit.

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Exchange).

Introduction

Context

Extensively grazed heathlands in the uplands of the UK are internationally important for their conservation value (Thompson *et al*., 1995) including invertebrates (e.g. Usher, 1992) and upland bird communities dependent on them (Buchanan *et al*., 2006), and are a key resource in supporting upland farmland economies and providing ecosystem services (Bonn *et al*., 2009). Targets for the enhancement and maintenance of these habitats have been established within the UK Biodiversity Action Plan (BAP) and the UK Post-2010 Biodiversity Framework, and the majority of sites have been designated as Sites of Special Scientific Interest (SSSIs) and in many cases Special Areas of Conservation (SACs). Heather moorland in the UK holds a unique assemblage of bird species, including several species listed in Annex 1 of the EC Birds Directive 79/409/EEC. However, economic pressures and agricultural subsidies in the second half of the 20th century resulted in major increases in the numbers of sheep being kept in upland areas. As a result of this and previous high stocking densities, semi-natural vegetation became overgrazed with a decline in dwarf shrub species such as *Calluna vulgaris* and *Vaccinium myrtillus* (Bardgett *et al*., 1995) and replacement by grasses including *Nardus stricta* (Welch & Scott, 1995) with consequent effects on other biodiversity including invertebrates (Littlewood *et al*., 2006; Dennis *et al*., 2008).

Reduced sheep stocking rates encouraged under agri-environment schemes from the late 1980s were intended to reverse these changes (Condliffe, 2009) but in dense grassy swards restoration of dwarf shrubs is often inhibited by competition and the absence of gaps for regeneration. Cattle could have a role in restoring *N. stricta* dominated swards, as they consume more *N. stricta* than sheep (Common *et al*., 1998; Fraser *et al*., 2009) and have potential to create more gaps from trampling. However, if *C. vulgaris* is scarce or absent, then more interventionist methods are required, including seed introduction, gap creation and appropriate grazing regimes (Marrs *et al*., 2004). Under Countryside Stewardship, options for management of moorland (Higher Tier Option UP3) require moorland to be grazed to an agreed stocking calendar, which specifies the timing, species and numbers of livestock (Natural England, 2016a). Supplements are also available to remove livestock for periods of time to aid moorland restoration including regeneration of *C. vulgaris* (Higher Tier Option UP6) and to introduce cattle into the system (Mid Tier Option SP6) (Natural England, 2016b). Although some effects of grazing on moorland vegetation are well understood, there are still significant knowledge gaps and better evidence is needed on the effects of different grazing regimes on moorland habitats (Martin *et al*., 2013). To assist in the formulation of suitable guidelines for these options, there is a need to identify appropriate grazing regimes and other techniques to restore dwarf shrub heathland on *N. stricta* grasslands, whilst maintaining acceptable levels of livestock performance and benefiting the wider moorland biodiversity.

Previous work

Under Defra project BD1228, one of the objectives was to 'Assess, through system scale and plot scale studies, the impact of selected grazing regimes and intervention techniques on vegetation, livestock and economic viability, and invertebrate groups of conservation importance'. A range of sustainable grazing regimes for the restoration and maintenance of heather moorland habitats was identified and their ecological and economic impacts assessed (Critchley *et al.*, 2007). That project included system scale studies of sheep, cattle and mixed grazing regimes and plot-scale restoration experiments on degraded *N. stricta* moorland at ADAS Pwllpeiran over a four-year period. The Pwllpeiran study was then extended until 2010 under project BD1243 (ADAS, 2011). From 2010 until the start of this phase of the study in 2012, the site was not grazed.

Performance of both sheep and cattle in the four different grazing treatments applied at Pwllpeiran was adequate for commercial application. Predictions from models developed under BD1228 suggested that in the long-term, *N. stricta* was likely to decline, especially under sheep-only grazing at low stocking densities. By 2010, there were indications that this process might have started, although the changes were very slow, and needed to be confirmed over a longer period. Model predictions from BD1228 also indicated that rotational grazing regimes had potential for reducing *N. stricta* and increasing heathland species including *V. myrtillus*. However, the different grazing regimes have shown varying benefits for biodiversity. In the paddock-scale system studies, several invertebrate groups (including some that are important in the diet of moorland birds) declined under cattle grazing treatments but cattle were also beneficial because they grazed *V. myrtillus* less than sheep and reduced *Molinia caerulea*.

The plot-scale restoration experiments showed the best treatments to re-establish *C. vulgaris* were seed addition plus disturbance, and either no grazing or cattle-only grazing. However, although Countryside Stewardship allows exclusion of livestock in heather restoration schemes, livestock will usually need to be re-introduced after initial establishment of *C. vulgaris* to maintain the economic viability of moorland management. Currently, it is not known how newly-established *C. vulgaris* and other vegetation will respond when grazing recommences. In restoration schemes where livestock exclusion is not practical, it will also be necessary to know the long-term response under different grazing regimes.

In this project, the following questions were addressed that will have application for moorland management and restoration in similar upland areas across the UK:

1. What are the long-term effects of rotational sheep, cattle and mixed grazing regimes on the sward composition of degraded *N. stricta* moorland?
2. Do the differences in invertebrate abundance detected previously persist in the longer term?
3. Is livestock performance maintained at an acceptable level in the longer term?
4. Can grazing be re-introduced in heather restoration schemes after the initial period of grazing exclusion?
5. What are the long-term effects of sheep, cattle and mixed grazing regimes on heather restoration?

Objectives

The general aim of the project was to acquire additional long-term data from the grazing system study paddocks and heather restoration plots established at Pwllpeiran under BD1228 in 2002 and continued under BD1243 until 2010. The objectives of this project were to:

1. Reintroduce the grazing regimes on the 12 replicated treatment paddocks in 2013 and continue for a further 3 years (4 years in total).
2. Measure impacts on livestock performance under the different grazing regimes.
3. Repeat vegetation assessments in 2012 and 2016, to identify long-term effects of the different grazing regimes at the paddock scale, following a 2-year period where grazing was excluded.
4. Repeat invertebrate sampling in 2016, to identify long-term effects of the different grazing regimes.
5. Introduce grazing to a subset of the heather restoration plots not grazed since the start of the experiment, and repeat heather assessments in 2012 and 2016 under the different grazing regimes.

Methods

Study site and grazing treatments

The site comprised 72 ha of *N. stricta* grassland (similar to the *Nardus stricta* – *Galium saxatile* (U5) community; Rodwell, 1992), which was formerly dwarf shrub heath but degraded by past heavy grazing. The main objective was to reduce the abundance of *N. stricta,* to restore dwarf shrubs such as *V. myrtillus* and *C. vulgaris*, and maintain the diversity of other plant species. The area was divided into three blocks, each subdivided into four paddocks (12 paddocks in total). Four grazing treatments were applied from spring 2003 to autumn 2010, allocated randomly to paddocks and replicated over the three blocks. Treatments were low sheep (LS; 1.0 ewes per ha[a] for 10 months per year + lamb from May to August), high sheep (HS; 1.5 ewes per ha[b] for 10 months per year + lamb from May to August), cattle only (CO; 0.5 heifers per ha[c] for 2 months in summer only) and mixed sheep plus cattle grazing (SC; low sheep + cattle). Welsh Mountain ewes and yearling Welsh Black heifers were used. From 2010 to 2012 none of the paddocks was grazed, and the grazing regimes were then reintroduced for a further four years from 2013 to 2016. The regimes during the final four years were modified because they were applied by an independent grazier and it was not possible to exactly replicate the regimes applied when the site was occupied and managed by ADAS. During this period, ewes were taken off the paddocks for tupping as previously, but were not returned over winter. Full details of the system study, including detailed description of methods and results are in Appendix 1.

The plot experiments were located in paddocks with three of the grazing treatments, being HS, CO and SC. In each paddock, six 10 x 10 m plots were established in 2002 in areas with similar vegetation, totalling 54 plots. Plots were randomly assigned to one of three disturbance treatments (undisturbed, rotavation and trampling) carried out in September 2002, with each disturbance treatment replicated twice per paddock. Rotavation treatments were followed by harrowing to bundle up the litter created by the rotavation. The trampling treatment was carried out by herding five Welsh Black bulling heifers until about 25% of the plot had been trampled. All plots then had two sub-treatments applied to them in March 2003. *C. vulgaris* seed was mixed with silver sand and broadcast by hand at a rate of 0.8 g seed m^{-2} (26,000 seeds m^{-2}) on half of each plot. A no-grazing treatment was applied by fencing half of each plot perpendicular to the seeding treatment, to create a 2 x 2 factorial structure: (a) grazed, not seeded, (b) not grazed, not seeded, (c) not grazed, seeded and (d) grazed and seeded. From 2010 until 2012 all plots were ungrazed. In 2012 the fencing on half of the plots was then swapped over. As each paddock had two plots for each of the 3 disturbance treatments the fencing on one of each of the disturbance treatments was swapped. Thus the

[a] *n* = 5-7 ewes per paddock
[b] *n* = 9-11 ewes per paddock
[c] *n* = 4 heifers per paddock

half that was fenced from 2002-2012 became unfenced and the half that was unfenced became fenced. Due to the switching of fencing in 2012 the fencing history is shown as a three letter code (Table 1). For simplicity, GUG is sometimes described as 'always grazed'. Full details of the restoration plots, including detailed description of methods and results are in Appendix 2.

Table 1. Fencing history codes.

Code	Grazing treatment		
	2002-2010	2010-2012	2012-2016
UUU	U (ungrazed)	U (ungrazed)	U (ungrazed)
UUG	U (ungrazed)	U (ungrazed)	G (grazed)
GUG	G (grazed)	U (ungrazed)	G (grazed)
GUU	G (grazed)	U (ungrazed)	U (ungrazed)

Vegetation

A grid of 1 x 1 m fixed quadrats at 75 m spacing was superimposed on the 12 paddocks and vegetation recorded at each point from a fixed 1 x 1 m quadrat subdivided into 100 cells of 10 x 10 cm. Data were available for analysis from 124 quadrats in this phase of the project (2012 – 2016). Percentage top cover of plant species, plant litter and bare peat was estimated using a sighter with cross-wires in the centre of each cell and presence of all plant species also recorded. The presence of four key species (*N. stricta*, *V. myrtillus*, *C. vulgaris*, *Molinia caerulea*) in each 10 cm cell (local frequency) was recorded, along with the presence of any grazed shoots of these species in each cell. The maximum sward height at each of five random locations within each quadrat was measured using a sward stick and coefficients of variation in height calculated at both paddock and local scales (the latter from the five measurements per quadrat). Vegetation recording in the paddocks was done during 5th to 23rd October 2012 and 19th October to 3rd November in 2016. Data from 2012-2016 were analysed by multivariate repeated-measures Analysis of Variance (ANOVA) and treatment effects on grazing indices (percentage of shoots grazed) in 2016 were analysed using a mixed model Analysis of Variance. Treatment effects on the whole plant community were analysed by Partial Redundancy Analysis (pRDA).

Invertebrates

Pitfall traps had been used to obtain activity-density estimates of epigeal invertebrates at the soil surface in 2006 and in 2010. This was repeated in 2016 to obtain estimates at the end of the four-year period when grazing was re-introduced. At each of two randomly selected quadrat locations per paddock, five pitfall traps were sunk into the soil, with 1m between traps. Ethylene glycol was used as a preservative in the base of each trap. Traps were in place for two sessions from 4 July to 3 August and 7 September to 4 October and emptied at the end of each session. Individual adults and larvae (if present) were sorted and counted in major taxonomic groups. Effects of grazing treatments and vegetation composition (sample scores from the first two axes of a Principle Components Analysis (PCA) of 2016 plant species cover at each invertebrate sampling location) and height on the invertebrate groups were analysed by pRDA, and treatment effects on individual groups using a mixed model Analysis of Variance.

Livestock performance

Livestock data were recorded each year from 2013 to 2016. Liveweight and body condition scores were recorded for all heifers when turned onto and removed from the paddocks. Liveweights and body condition scores were recorded for ewes when turned out after lambing and at weaning in early September. Lambs were also weighed when turned out, at shearing in late June and at weaning. Changes in livestock weights and condition scores each year were analysed using repeated-measures Analysis of Variance.

Heather restoration plots

A 4 x 4m sub-plot was established in each quarter plot and further divided into four 2 x 2m and sixteen 1 x 1m quadrats for recording vegetation variables in September 2012 and September 2016. Up to four shoots of *C. vulgaris* were selected randomly from a 1 x 1m quadrat, and the overall height, length of the current year's growth increment and browsing of the current or previous year's growth recorded from each shoot. In each of the sixteen 1 m^2 quadrats in each sub-plot, vegetation height was measured using a drop disc. Plant species and bare ground cover were estimated by eye in one permanently marked 4 m^2 quadrat in each sub-plot and the percentage cover of *C. vulgaris*, dead *C. vulgaris* and *Juncus effusus* was recorded in each 2 x 2m quadrat.

Continuous variables were analysed by fitting linear mixed models with differences between individual pairs of treatments tested using least squared means and adjusted using the Tukey-Kramer correction for multiple tests. Frequency data (*J. effusus*) were analysed by fitting generalized linear mixed models. The composition of the experimental plots in 2012 and 2016 was compared to the target communities using a modified Bray and Curtis similarity index. Changes in community composition over time were assessed using Principal Response curves analysis (PRC). Further details are in Appendix 2.

Results

Vegetation

In 2012 after the period without grazing, the LS treatment had a significant effect on species frequencies (percentage of quadrats per paddock in which they occurred) (P<0.05), and there was also a statistically significant effect of the four grazing treatments collectively (P<0.05). In 2016 following re-introduction of grazing, LS still had a significant effect on the plant species frequencies (P<0.05), although the overall effect of the four treatments collectively was no longer significant. The mosses *Hylocomium splendens*, *Pleurozium schreberi* and *Polytrichum* sp. tended to be associated with LS, as did the palatable grasses *Agrostis capillaris* and *Festuca rubra*. In contrast, the mire vegetation was less associated with LS (as indicated by, for example, *Eriophorum vaginatum*, *E. angustifolium*, *Sphagnum* spp. and *Trichophorum germanicum* (Figure 1).

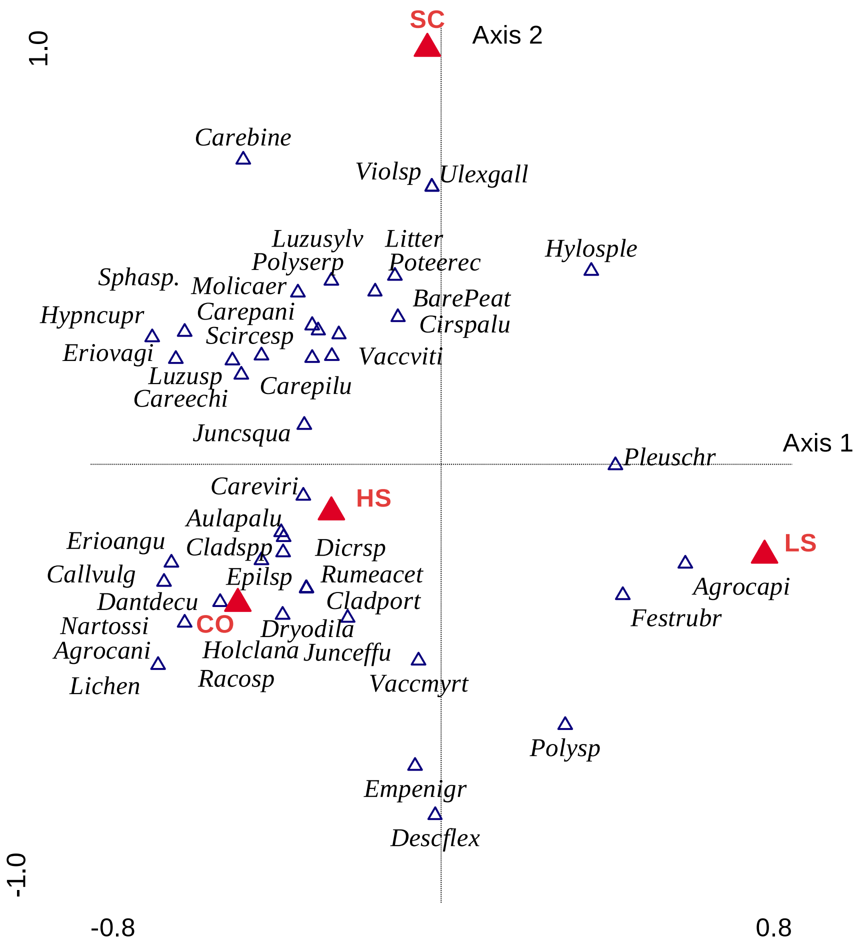

Figure 1. pRDA biplot of plant species frequencies and grazing treatments in 2016. Only species with fit >=10% shown for clarity. Treatment codes: LS = low sheep only; HS = high sheep only; SC = sheep plus cattle; CO = cattle only. Species codes: Agrocani = Agrostis canina; Agrocapi = Agrostis capillaris; Callvulg = Calluna vulgaris; Carebine = Carex binervis; Careechi = Carex echinata; Carepani = Carex panicea; Carepilu = Carex pilulifera; Careviri = Carex viridula agg.; Cirspalu = Cirsium palustre; Cladport = Cladonia portentosa; Cladspp = Cladonia spp; Dantdecu = Danthonia decumbens; Descflex = Deschampsia flexuosa; Dicrsp = Dicranum sp.; Dryodila = Dryopteris dilatata; Epilsp = Epilobium sp.; Empenigr = Empetrum nigrum; Erioangu = Eriophorum angustifolium; Eriovagi = Eriophorum vaginatum; Festrubr = Festuca rubra; Holclana = Holcus lanatus; Hylosple = Hylocomium splendens; Hypncupr = Hypnum cupressiforme; Junceffu = Juncus effusus; Juncsqua = Juncus squarrosus; Luzusp = Luzula sp.; Luzusylv = Luzula sylvatica; Molicaer = Molinia caerulea; Nartossi = Narthecium ossifragum; Pleuschr = Pleurozium schreberi; Polyserp = Polygala serpyllifolia; Polysp = Polytrichum sp.; Poteerec = Potentilla erecta; Racosp = Racomitrium sp.; Rumeacet = Rumex acetosa; Scircesp = *Trichophorum germanicum*; Sphasp = Sphagnum sp.; Ulexgall = Ulex gallii; Vaccmyrt = Vaccinium myrtillus; Vaccviti = Vaccinium vitis-idaea; Violsp = Viola sp.

During the period with no grazing, there was a non-significant declining trend (P=0.06) in *N. stricta* frequency from 37.6% in 2010 to 30.8% in 2012 (Table 2). This apparent reduction occurred across all treatments, there being no significant year x treatment interaction. A significant decline had been recorded previously from 51.4% in 2003 to 36.8% in 2005, and this represented a further reduction. *M. caerulea* was only present at low frequencies but showed a significant increase from 4.4% to 6.7% across all treatments during the no-grazing period. Top covers of species groups were closely similar in 2010 and 2012, indicating there had been no gross changes since grazing ceased. Mean vegetation height showed a non-significant increasing trend (P=0.06) across all treatments during the period without grazing, but only by *c.* 2cm (from 15.5 cm in 2010 to 17.4 cm in 2012). Height variability at the local scale also showed an overall declining trend (P=0.06). Height variability at the paddock scale appeared to increase in the SC treatment (significant year x treatment interaction) but also declined slightly in the HS and CO treatments.

Table 2. Mean (±SE) local frequency of key species, top cover of species groups and vegetation structure variables in 2010 and 2012, with F statistics from repeated-measures ANOVA. Untransformed data presented for clarity. $^{(*)}$ P<0.1, * P<0.05, ns = not significant.

Variable	**2010**		**2012**		**Year**	**Year x treatment**
					$F_{1,6}$	$F_{3,6}$
Key species frequency						
Calluna vulgaris	1.7	±0.88	2.2	±1.24	0.9 ns	0.3 ns
Molinia caerulea	4.4	±1.02	6.7	±1.38	11.5*	1.6 ns
Nardus stricta	37.6	±3.29	30.8	±3.16	5.5$^{(*)}$	0.1 ns
Vaccinium myrtillus	52.1	±3.34	57.0	±4.87	3.1 ns	0.2 ns
Top cover of species groups						
Dwarf shrubs	10.6	±0.92	9.5	±1.09	2.5 ns	0.2 ns
Graminoids	64.8	±1.30	67.1	±2.64	0.9 ns	0.5 ns
Bryophytes	18.3	±0.96	18.9	±1.91	0.0 ns	0.2 ns
Forbs	3.4	±0.41	3.4	±0.50	0.2 ns	1.9 ns
Vegetation structure						
Mean height	15.5	±0.86	17.4	±1.02	5.2 $^{(*)}$	1.8 ns
Paddock-scale CV	0.31	±0.030	0.31	±0.016	0.0 ns	8.2*
Local-scale CV	0.34	±0.020	0.29	±0.013	5.2 $^{(*)}$	1.6 ns

No changes were detected in the local frequencies of key species from 2012 to 2016, and this was consistent among treatments for all species (as indicated by the year x treatment interactions, which were not significant). However, overall during this period there was a significant treatment effect on *C. vulgaris* frequency (P<0.05), with greatest mean frequency in CO (10.5 ±0.36% SE) compared to means of 0.1% – 3.6% in the other treatments. Frequency of *N. stricta* was very similar in 2012 and 2016, which followed the overall decline in frequency in previous years of the study.

Background grazing levels on key species in 2012 were negligible in the absence of livestock. In 2016, overall grazing levels were very low on *C. vulgaris* (0.0 – 3.0 ±3.03% SE), *M. caerulea* (0.9 ±0.73 – 11.3 ±5.29%) and *N. stricta* (0.0 – 0.8 ±0.32%), but were higher on *V. myrtillus* (10.0 ±1.40 – 13.8 ±4.08%). However, no differences were detected among treatments in the levels of grazing on any of the key species.

Graminoids had the highest top cover values of all species groups in both 2012 and 2016, and increased significantly from *c.* 67% to *c.* 80% following the re-introduction of grazing (Table 3). However, the palatable grasses subset showed no change, indicating that it was primarily the less palatable species that had increased. Conversely, covers of bryophytes, dwarf shrubs and forbs all decreased following re-introduction of grazing. The changes in covers of the species groups were consistent among treatments (none of the year x treatment interactions was significant).

The cover of several species analysed also changed between 2012 and 2016. Cover of *E. vaginatum* increased by a small amount, from *c.* 4% to 5.6%. In contrast, there were small but significant decreases in the covers of *V. myrtillus*, the mosses *P. schreberi* and *Rhytidiadelphus squarrosus* and the forb *G. saxatile*. Notably, there was a non-significant upward trend in the cover of *N. stricta* from *c.* 17% to *c.* 22% (P =

0.08). The year x treatment interactions indicated that all these changes occurred consistently among the four treatments, with the exception of *R. squarrosus*, which declined in all treatments apart from SC. *C. vulgaris* cover was higher in the CO treatment than the other treatments during 2012 and 2016 (treatment $F_{3,5}$ = 7.5, P <0.05) but no other treatment effects on other species or species groups were detected.

Table 3. Mean (±SE) top cover of species groups and key species in 2012 and 2016, with F statistics from repeated-measures ANOVA. Untransformed data presented for clarity. * P<0.05, ** P<0.01, *** P<0.001, ns = not significant.

Variable	**2012**		**2016**		**Year**	**Year x treatment**
					$F_{1,5}$	$F_{3,5}$
Dwarf shrubs	9.8	±1.20	7.25	±0.75	9.0*	0.7 ns
Graminoids	66.9	±2.72	80.1	±1.99	47.0**	0.4 ns
Bryophytes	19.2	±2.13	10.3	±1.78	70.7***	0.7 ns
Forbs	3.3	±0.45	1.3	±0.21	18.3**	0.7 ns
Palatable grasses	23.6	±1.90	26.7	±2.76	2.9 ns	0.6 ns
Calluna vulgaris	1.4	±0.74	2.0	±0.88	0.2 ns	2.3 ns
Deschampsia flexuosa	3.5	±0.99	5.1	±1.13	2.6 ns	0.3 ns
Eriophorum vaginatum	4.0	±0.94	5.6	±1.27	10.7*	2.0 ns
Festuca ovina	6.4	±0.58	5.5	±0.62	0.3 ns	0.2 ns
Galium saxatile	1.4	±0.14	0.8	±0.14	18.0**	0.3 ns
Juncus squarrosus	3.5	±0.86	4.4	±1.06	4.2 ns	1.3 ns
Molinia caerulea	2.5	±0.73	2.1	0.81±	0.3 ns	3.4 ns
Nardus stricta	17.3	±2.14	22.1	±2.22	4.8 ns	0.3 ns
Pleurozium schreberi	4.4	±0.81	0.72	±0.15	32.3**	0.5 ns
Rhytidiadelphus squarrosus	2.6	±0.45	1.5	±0.34	113.1***	15.8**
Vaccinium myrtillus	7.7	±1.06	4.5	±0.64	22.5**	0.2 ns

There was a significant decline in mean vegetation height across all paddocks of *c*. 4 cm (from 17.9 cm to 14.0 cm) during the 4-year period following re-introduced grazing in 2012 (P<0.01). The decline was consistent across treatments (time x treatment interaction was not significant). This followed the increasing trend of *c.* 2 cm in mean height during the period without grazing earlier in the study. However, there were no changes in coefficients of variation in height at either spatial scale, nor did this vary among treatments.

Invertebrates

In July, the groups with highest activity-density indices were Hymenoptera, Araneae and Coleoptera. Activity-density indices were lower in September, but the groups with highest indices then were Araneae, Coleoptera and Diptera.

None of the environmental variables had a significant effect on the invertebrate groups in July, nor did they have a significant effect collectively. However, in September the vegetation PCA axis 1 (P<0.05) and the SC treatment (P<0.05) both had a significant effect on invertebrate groups. There was also a weak non-significant effect (P<0.1) of CO and mean vegetation height, and of LS (the latter being significant only after adding the previous variables to the model). Vegetation PCA axis 1 represented a gradient from mire vegetation at the positive end (including *Eriophorum* spp, *M. caerulea*, *Sphagnum* spp., *C. vulgaris*, *Erica tetralix*, *Narthecium ossifragum* and *Trichophorum germanicum*), to acid grassland vegetation at the negative end (including *A. capillaris*, *N. stricta*, *Carex pilulifera*, *Potentilla erecta*, *Hypnum cupressiforme*, and *F. ovina*). All invertebrate groups tended to be more associated with the grassland rather than the mire vegetation, the strongest effect being on Acarina, Mollusca, Coleoptera, Hemiptera and Collembola (Figure 2). In addition, most groups tended to be less associated with SC compared to all the other treatments; the strongest effect was on Collembola, Diptera larvae and Hemiptera. Mean vegetation height was correlated with the third pRDA axis (not shown); Chiloptera, Coleoptera larvae and Mollusca tended to be associated with shorter rather than taller vegetation. All treatments collectively also had a significant effect on invertebrate captures in September (P<0.01).

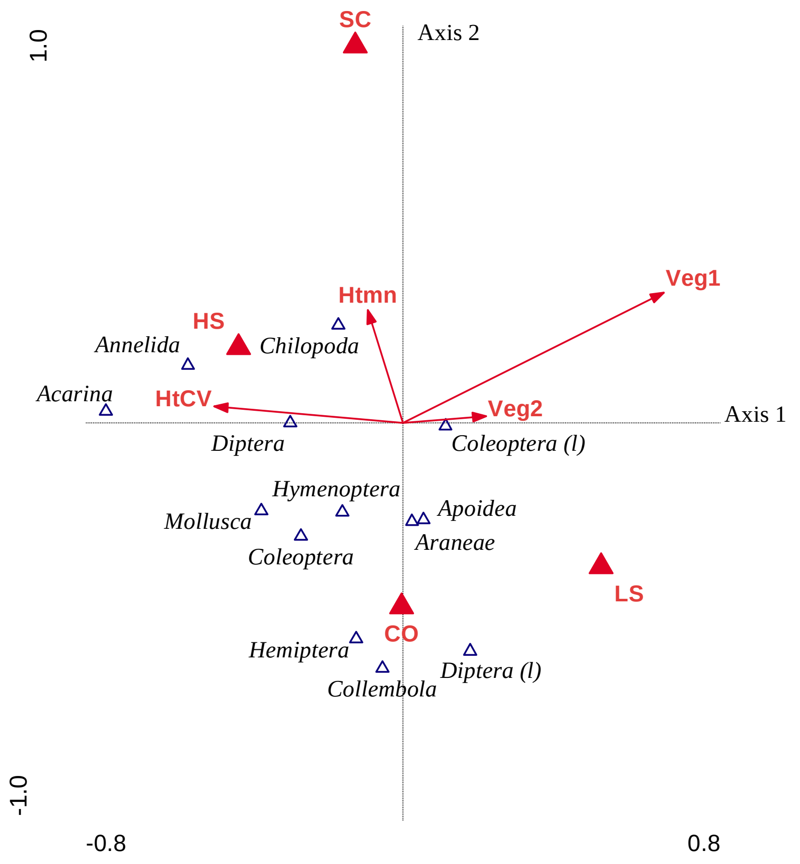

Figure 2. pRDA biplot of invertebrate captures (l = larvae, otherwise adults) and grazing treatments and vegetation variables in September 2016. Environmental variable codes as Figure 1, plus Veg1 = vegetation PCA axis 1 score; Veg2 = vegetation PCA axis 2 score; Htmn = mean vegetation height, HtCV = vegetation height coefficient of variation.

No significant treatment effects were detected on taxonomic groups individually apart from Collembola in September, when activity-density was highest in LS and lowest in SC ($P<0.05$). A similar non-significant trend was also present for Coleoptera in September ($P=0.054$). Mean values for most other groups tended to be higher in the sheep only (especially LS) than CO or SC, albeit with high variability around the means. Exceptions to this general pattern were Mollusca and Annelida in both months. An analysis of total captures across all groups showed no significant treatment effect in either July or September.

Livestock

Cattle liveweights increased significantly during the period of grazing on the paddocks in each of the three years 2013 ($P<0.001$), 2014 ($P<0.001$) and 2015 ($P<0.01$). In 2016, there was also a non-significant increasing trend ($P = 0.052$) (although note there was reduced statistical power in 2016 due to missing data). No significant effect of treatment on weight change was detected in 2014, 2015 or 2016. In 2013, a significant change x treatment interaction ($P<0.05$) showed that although weights increased in both treatments, the increase was slightly greater in the CO treatment than SC. Cattle condition scores also improved each year between turning out and removal from the paddocks ($P<0.05$). There was no overall effect of treatment on condition scores at the end of the grazing period each year. In 2014 only, condition scores increased in the SC treatment but not in CO (change x treatment $P<0.05$). However, scores tended to be lower in SC than CO at the start and were similar in the two treatments by the end of the grazing period.

A comparison of cattle daily liveweight gains since the start of the extended study in 2003 showed considerable annual variation (Table 4). For example, the lowest gains were in 2016 whereas liveweight gains in 2013 were exceptionally good, and followed the two-year period when the site was not grazed. Differences between the two treatments also varied from year to year.

Table 4. Cattle mean daily liveweight changes (kg day^{-1}) throughout the extended study.

	2003	2004	2005	2006	2007	2008	2009	2010	2013	2014	2015	2016
CO	0.45	0.41	0.76	0.50	0.59	0.77	0.75	0.25	0.87	0.18	0.28	0.09
SC	0.59	0.31	0.69	0.36	0.63	0.56	0.63	0.04	0.57	0.21	0.32	0.08
Mean	0.52	0.36	0.73	0.43	0.61	0.67	0.69	0.15	0.72	0.19	0.30	0.09

Change in ewe liveweights, from onset of grazing after lambing until weaning, was variable from year to year. In 2013, immediately following the two-year period with no grazing, ewe liveweights increased significantly ($P<0.05$). In contrast, liveweights declined in both 2014 ($P<0.001$) and 2016 ($P<0.01$), whereas there was no significant change in 2015. There was no treatment effect on ewe weight change in any year from 2013 to 2016. Change in ewe condition scores also varied from year to year. In 2013 and 2016, condition scores increased significantly from the start of grazing after lambing until weaning ($P<0.05$), but there was no significant change in 2014 or 2015. The improvement in condition in 2016 occurred despite an overall decline in liveweights.

A comparison of ewe weaning weights since the start of the study showed a notable degree of annual variation, most likely attributable to weather conditions and availability and quality of forage. There were no significant treatment effects on weaning weight in any single year from 2013 to 2016, nor had there been any treatment effect during the earlier period of the study.

Lamb liveweight gains, between turning out to the paddocks and weaning, were affected by treatment in 2013 and 2016 (Table 5). In both years, liveweight gains were least in HS. In 2013 only, gains in SC were greater than in the other treatments (unequal N HSD $P<0.05$). However, there was no significant difference in weight gain among treatments in either 2014 or 2015.

Over the course of the extended study, lamb mean weaning weights varied from 23.8 kg in 2004 to 31.9 kg in 2007. There was no significant treatment effect on weaning of weights of lambs in any of the four years from 2013 to 2016, nor had there been in the previous years of the extended study.

Table 5. Mean (±SE) lamb liveweights (kg) on the paddocks and at shearing and weaning each year from 2013 to 2016. * $P<0.05$, ** $P<0.01$. *** $P<0.001$, ns = not significant, nd = no data.

	2013	2014	2015	2016
Weight on	14.6 ±0.33	15.7 ±0.31	15.7 ±0.37	12.9 ±0.25
Shearing weight	21.4 ±0.47	25.5 ±0.41	27.4 ±0.42	nd
Weaning weight	25.7 ±0.51	29.5 ±0.45	29.2 ±0.46	24.3 ±0.34
Change x Treatment *F*	4.3**	1.4 ns	0.8 ns	4.5*
df	4,114	4,130	4,132	2,57

Heather restoration plots

<u>*C. vulgaris* cover</u>

C. vulgaris cover in the 2 m x 2 m quadrats (4 quadrats per sub-plot) in 2016 was significantly affected by grazing ($P<0.01$), disturbance ($P<0.0001$), fencing history ($P<0.01$) and seeding ($P<0.0001$) (Figure 3). There was no significant interaction between any of these effects. Similarly, change in *C. vulgaris* cover between 2012 and 2016 (years 10 and 14 of the experiment) was also significantly affected by fencing history ($P<0.0001$), disturbance ($P<0.01$), and seeding ($P<0.0001$).

Current grazing had a detrimental effect on *C. vulgaris* cover irrespective of whether grazing had been applied previously. Likewise, where grazing was removed, *C. vulgaris* cover had recovered to levels similar to those in plots that had never been grazed. Several comparisons provided evidence for these findings. The UUG treatment had significantly less *C. vulgaris* cover than UUU ($P<0.05$) and its *C. vulgaris* cover was not significantly different from that in GUG ($P>0.05$). *C. vulgaris* cover in treatment GUU was not significantly different from that in UUU ($P>0.05$). In addition, *C. vulgaris* cover increased the most in GUU and declined in UUG.

The results from the other main treatments showed the same patterns as in previous visits. There was significantly greater *C. vulgaris* cover in the cattle only grazing treatment than in the sheep only or mixed grazing treatment ($P<0.05$) and significantly greater *C. vulgaris* cover in rotavated or trampled plots than in undisturbed plots ($P<0.05$). Seeded sub-plots also had significantly greater cover than unseeded sub-plots. In addition, *C. vulgaris* cover increased most in cattle grazed sub-plots and the least in those subjected to sheep grazing. It also increase more in rotavated or trampled plots than control plots, and more in seeded than unseeded plots.

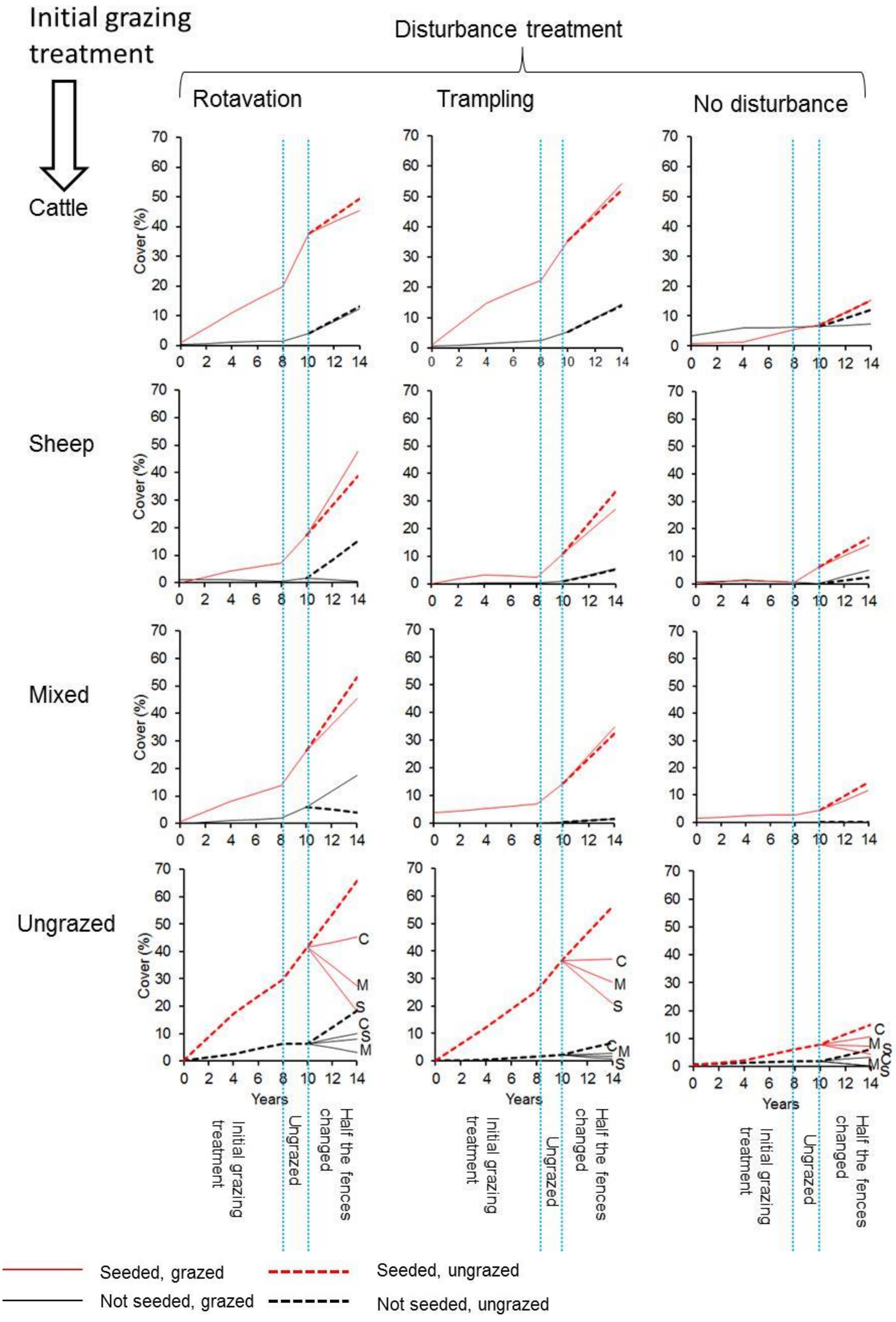

Figure 3. Cover of *C. vulgaris* over 14 years of restoration treatments. On the graphs for the ungrazed subplots C = cattle, M = mixed and S = Sheep to indicate the type of grazing introduced once half the fences were swapped over.

C. vulgaris height

Both grazing (*P*<0.0001) and fencing history (*P*<0.0001) had a significant effect on *C. vulgaris* height. Sub-plots with cattle and mixed grazing had significantly taller *C. vulgaris* than sheep grazed sub-plots (*P*<0.05). Additionally, UUG and GUG treatments had significantly shorter *C. vulgaris* than UUU and GUU (*P*<0.05).

There was also a significant interaction between grazing and fencing history (*P*<0.05). The average height of the *C. vulgaris* in ungrazed plots was 25 cm. The average height in the sheep grazed plots ranged from 10 cm to 19 cm depending on the combination of fencing over the three time periods. *C. vulgaris* in UUG and GUG treatments was significantly shorter than in UUU or GUU (*P*<0.05). However, *C. vulgaris* height in GUU was not significantly different from that in UUU. In cattle grazed plots the average heather height ranged from 17 cm to 24 cm depending on the combination of fencing over the three time periods, although the differences between fencing history within the cattle grazing were not significant. In the mixed grazing plots the average *C. vulgaris* height ranged from 17 cm to 27 cm, but the differences between fencing history within the mixed grazing were not significant.

C. vulgaris growth increments

Only fencing history had a significant effect on *C. vulgaris* growth increment (*P*<0.0001) with grazing being not quite significant (*P*=0.056). Plots that were currently grazed had smaller growth increments than plots that were currently ungrazed (Figure 4).

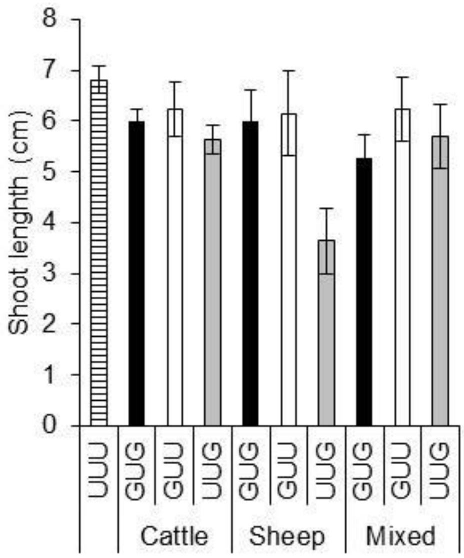

Figure 4. *C. vulgaris* growth increments under three grazing treatments (Cattle, Sheep and Mixed) with different combinations of fencing U = ungrazed, G = grazed. UUU = ungrazed for all 3 time periods.

Presence of *C. vulgaris* shoots

Plots that had previously been ungrazed but that were now grazed had significantly fewer *C. vulgaris* shoots present than plots with other fencing histories (*P*< 0.001). However, there were no differences between the grazing treatments in shoot numbers.

Vegetation height

In 2016 fencing history (*P*<0.01) and seeding (*P*<0.01) had a significant impact on the height of the vegetation. The vegetation in sub-plots that were currently ungrazed was significantly taller than sub-plots that were currently grazed. Of the sub-plots that were currently grazed, GUG had significantly taller vegetation than UUG.

Analysis of both 2012 and 2016 data showed that there was a significant effect of grazing (*P*<0.05), fencing history (*P*<0.0001), seeding (*P*<0.0001) and visit (*P*<0.0001) on vegetation height. There was also a significant interaction between fencing history, grazing and visit (*P*<0.001). Introducing grazing into previously ungrazed sub-plots resulted in a significant decline in vegetation height compared to 2012 irrespective of the type of grazing introduced (cattle, sheep or mixed). Removing grazing did not result in a significant increase in vegetation height in either the cattle or the mixed grazing sub-plots but removing sheep grazing did result in a significant increase. The lack of change in removing grazing in the cattle and mixed was thought to be because the change had already occurred prior to 2012 when there was no grazing for two years. This was tested by using identical analysis to assess the vegetation heights in 2010 and 2016. Once again this showed a significant interaction between fencing history, grazing and visit (*P*<0.001) and pair wise comparisons showed that removing of grazing resulted in the vegetation height being significantly taller in all three grazing treatments.

Similarity to target community

Seeded sub-plots were more similar to the target community with 50% *C. vulgaris* cover than unseeded ones (Figure 5; *P*<0.0001), which was consistent with results from previous years. There was also a significant difference between the disturbance treatments (*P*<0.0001) with rotavated and trampled plots being more similar than control plots to the target (*P*<0.001). Seeded disturbed sub-plots were also more similar to the target than seeded undisturbed sub-plots or unseeded disturbed sub-plots (seeding x disturbance interaction *P*<0.0001). However, neither grazing treatment nor fencing history had a significant effect on similarity to the target community.

The change in similarity index from both 2010 and 2012 to 2016 was calculated. Only fencing history was significant in explaining change in the similarity indices between 2012 and 2016 (*P*<0.05). Sub-plots with treatment GUU increased in similarity to the target more than UUG. In contrast fencing history (*P*<0.0001), disturbance (*P*<0.01), and seeding (*P*<0.0001) all explained the change in similarity indices between 2010 and 2016. Similarity to the target increased more in rotavated and trampled plots than undisturbed plots, in seeded than unseededand in GUU than UUG.

Changes in community composition

The principle response curves show community composition changes over time (years since the start of the experiment) compared to the control plots which were taken as the fenced, undisturbed, unseeded subplots in the cattle grazed paddocks. The response curves (Figure 6) all come from one analysis and as such are directly comparable; the curves are plotted on different graphs by grazing/disturbance treatment for reasons of clarity. Communities with a low Y axis score are dominated by *N. stricta, Festuca ovina, V. myrtillus* and *Agrostis* species and those communities at the high end of the Y axis are dominated by *C. vulgaris*. The response curves clearly show that under all grazing treatments plots that were disturbed (rotavated or trampled) and seeded sub-plots are further away from the grass dominated communities which occur higher up the graph. Notably in the sheep grazed and mixed grazed plots, the community changes to one that is more *C. vulgaris* dominated between years 8 and 10, which were the two years when the plots were released from grazing. However if grazing was then reintroduced (years 10-14), *C. vulgaris* cover declined.

Previous results showed that the disturbance treatments had a detrimental effect on other components of the community with the cover of *V. myrtillus* significantly lower on disturbed plots than undisturbed plots four years after the disturbance treatments had been carried out (Mitchell *et al.*, 2008). In contrast, after 14 years there was no significant difference between disturbance treatments in the cover of *V. myrtillus* but there was less *V. myrtillus* cover on seeded than unseeded sub-plots (*P*<0.001) and less on sub-plots that were currently grazed than on plots currently ungrazed (*P*<0.01).

The cover of *N. stricta* was influenced by grazing, disturbance , fencing history, and seeding. There was significantly greater cover of *N. stricta* in the sheep grazed plots than the mixed grazed plots (*P*<0.01), in the trampled than the control plots (*P*<0.01) and the unseeded than the seeded sub-plots (*P*<0.0001). Sub-plots with treatments GUU and GUG had a greater cover of *N. stricta* than UUU (*P*<0.0001). There were also significant interactions between disturbance and fencing history (*P*<0.05), and between disturbance and seeding (*P*<0.001). In plots that had always been ungrazed there was greater *N. stricta* cover in the undisturbed plots than in the rotavated or trampled plots. In rotavated and trampled plots, cover was greater in GUG than UUU. In contrast in undisturbed plots, cover in GUG was not different from that in UUU. Sub-plots that had either no seeding and/or no disturbance had greater cover of *N. stricta* than sub-plots that were disturbed (rotavated or trampled) and seeded.

After four years of the different grazing treatments *Agrostis* spp. cover had increased when grazed by sheep only, decreased in cover under the mixed grazing regime and remained unchanged in the cattle only grazing treatment (Mitchell *et al*., 2008). In 2016 there was no difference among grazing treatments in *Agrostis* spp. cover but it was lower in the GUU treatment than in UUG (*P*<0.05). *Agrostis* spp. cover was also lower in seeded than unseeded sub-plots (*P*<0.05).

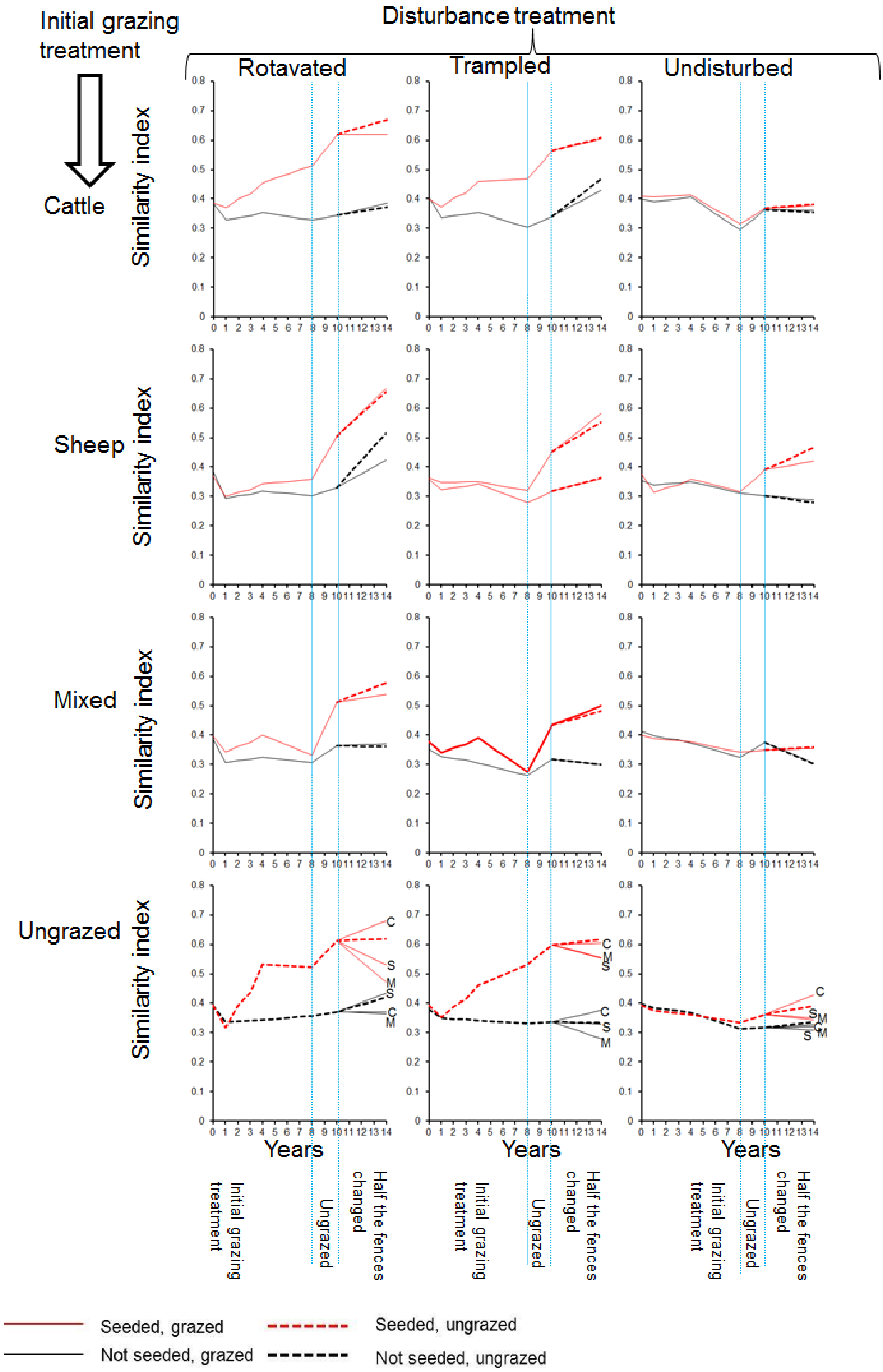

Figure 5. Similarity indices of experimental plots to a target community with 50% *Calluna vulgaris* cover. Scores range from zero if the communities have no species in common, to a maximum value of one when the communities are identical.

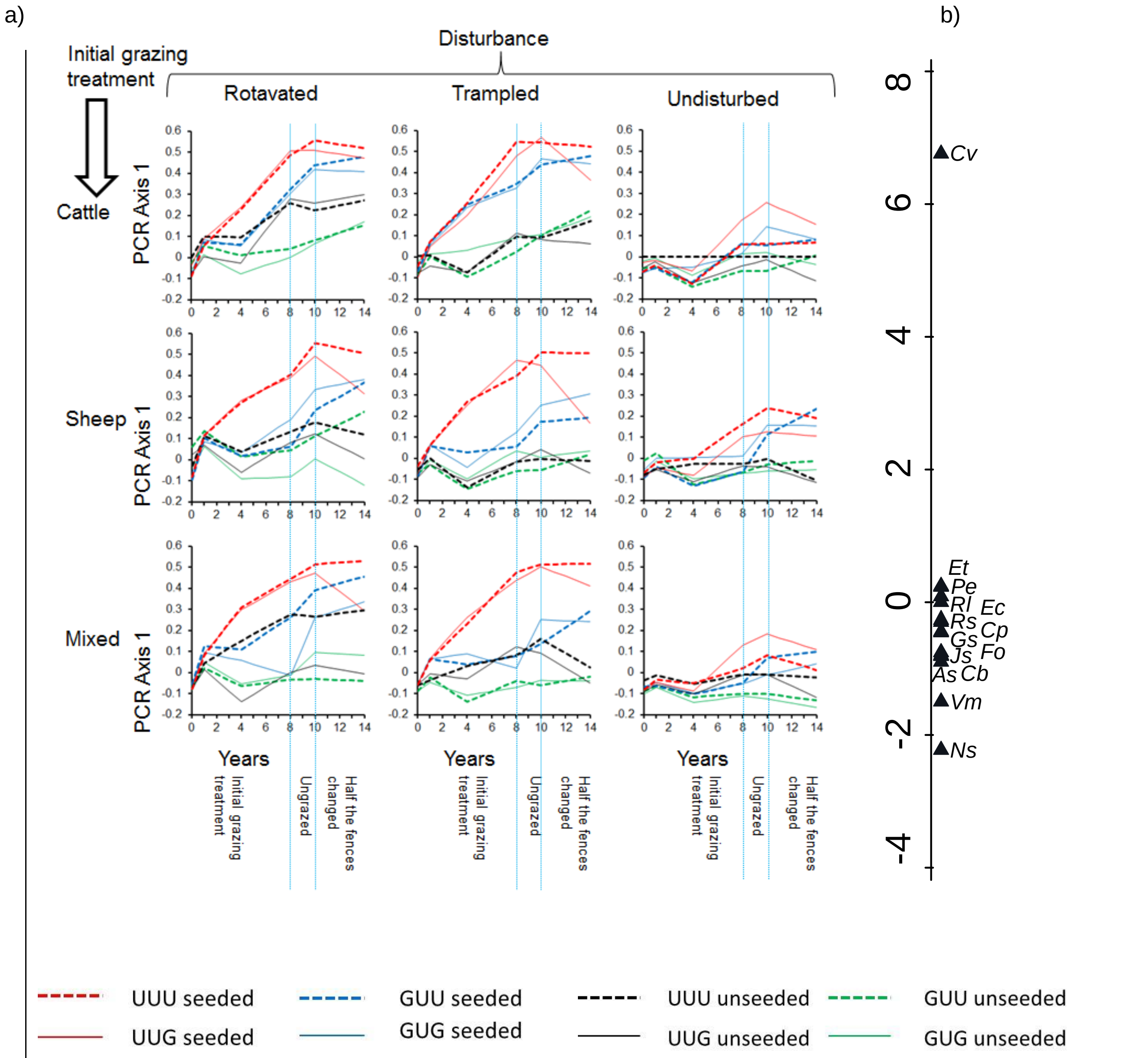

Figure 6. Principle response curves (PRCs) from an RDA analysis of community composition over time. Community changes are shown relative to control plots (ungrazed, undisturbed, unseeded sub-plots within the cattle grazing paddocks). a) Shows the PRC axis 1 against time (years since start of experiment) and b) shows the PRC axis 1 scores of the 13 species which explain the greatest amount of variation. As = *Agrostis* species; Cp = *Carex pilulifera*; Cv = *Calluna vulgaris*; Ec = *Erica cinerea*; Et = *Erica tetralix*; *Fo* = *Festuca ovina;* Gs = *Galium saxatile*; Js = *Juncus squarrosus*; *Ns* = *Nardus stricta;* Pe = *Potentilla erecta*; Rl = *Rhytidiadelphus loreus*; Rs = *Rhytidiadelphus squarrosus*; *Vm* = *Vaccinium myrtillus*. All graphs are from the same analysis but are shown by different grazing/distrubance treatments in the interest of clarity.

In contrast to *Agrostis* spp., *F. ovina* had decreased in cover in the sheep only grazing treatment but remained unchanged in the other grazing treatments after four years of grazing. In 2016 grazing had no effect on the cover of *F. ovina* but fencing history did (P<0.01). There was evidence that it was the previous grazing history as well as the current grazing that had an effect; there was lower cover of *F. ovina* in the GUG treatment than in UUG.

Results after 4 and 8 years since the start of the experiment showed that *Juncus effusus* cover and probability of being present were greater on disturbed plots (rotavated and trampled) than undisturbed plots (Mitchell *et al.*, 2008; Critchley *et al.*, 2013). However 14 years after the start of the experiment the disturbance treatments had no significant effect on either the probability of *J. effusus* being present or on its cover.

In 2016 disturbance (P<0.01), seeding (P<0.001) and fencing history (P<0.0001) had an effect on *Juncus squarrosus* cover. Cover was greater on unseeded than seeded sub-plots and on disturbed (rotavated or trampled) than undisturbed plots. In contrast to the results for other species, there was evidence that it was the previous grazing history not the current grazing that affected cover of *J. squarrosus*. GUG sub-plots had greater cover than UUG sub-plots and UUU had lower cover than GUG.

Discussion

Vegetation

The main aim of this phase of the experiment was to assess the effects of re-introducing grazing following a 2-year period when none of the paddocks was grazed. During the first period of grazing, there had been a decline in *N. stricta* frequency across all grazing treatments, and this trend continued during the two years without grazing. However, after re-introduction of grazing no further decline in *N. stricta* was detected, suggesting that it might have reached a stable level. Nonetheless, the overall decline from *c.* 51% local frequency at the beginning of the study to *c.* 33% some 13 years later does represent a positive change in the vegetation under relatively moderate levels of grazing intensity. Grazing levels on *N. stricta* were very low under all grazing treatments, so its decline was likely to be attributable to competition from other grasses as a result of the general reduction in grazing intensity compared to historic grazing levels on the site. However, the decline in frequency of *N. stricta* was not accompanied by a decline in its top cover. This suggests that *N. stricta* might be declining primarily in patches of vegetation where it is dispersed amongst other species but not where it is dominant, an effect consistent with model predictions from previous projects BD1211 and BD1228 (ADAS, 2002; Gardner *et al.*, 2009). At the paddock scale, there was no detectable effect on *N. stricta* of the grazing treatments, in contrast to the restoration plots where its cover was greater under sheep-only than mixed grazing. The greater spatial variability at the paddock scale would make it more difficult to detect more subtle differences due to the grazing treatments.

During the first phase of the experiment, no treatment effects had been detected on the frequencies of key species. However, both *C. vulgaris* and *M. caerulea* had been grazed more when cattle were present than in the sheep-only regimes. When grazing stopped, *M. caerulea* frequency increased although it was still relatively scarce and patchily distributed in the sward. Following re-introduction of grazing, *C. vulgaris* frequency and cover were greatest in the CO treatment. This effect had been apparent in the plot-scale restoration experiment since the start of the study (Mitchell *et al.*, 2008; Critchley *et al.*, 2013) but was also now manifest at the paddock scale, despite the greater spatial variability in vegetation at this scale. *V. myrtillus* declined in cover following re-introduction of grazing, and had relatively high grazing indices, suggesting that it might be vulnerable to grazing at the intensities applied in this study.

The changes in top covers demonstrated the short-term effects of grazing. During the no-grazing period, there was a surprising lack of change in covers of the species groups analysed, although small changes were apparent for some individual species. In contrast however, there were notable effects when grazing was re-introduced. Dwarf shrub cover declined, an effect consistent with results from the restoration plots which also showed that grazing reduced covers of both *C. vulgaris* and *V. myrtillus*. The decline in dwarf shrub and forb covers was probably attributable directly to defoliation, while the decline in bryophytes was more likely to be the result of trampling by livestock. The increase in graminoids, which was restricted to less palatable species that would tend to be avoided by livestock, is undesirable for both conservation and economic objectives. This was supported by results from the restoration plots that showed *J. effusus* tended to increase when plots were grazed. This suggests that the overall vegetation objectives will be difficult, or take longer, to achieve if grazing is applied even at these relatively moderate intensities.

The changes in mean vegetation height and height variability in response to both cessation and re-introduction of grazing were relatively small in magnitude. This reflects the low productivity of the vegetation and slow growth rates of the component species (Morecroft et al., 2016).

Overall, the results indicate that, at the paddock scale, the re-introduction of grazing *per se* had a greater effect on the vegetation than any differences among the four grazing treatments. However, during the earlier phase of the experiment when the paddocks had been grazed, the LS and SC grazing regimes had a significant effect on the overall plant species composition. In 2012 at the end of the no-grazing period, the LS treatment still had a detectable effect. This was also apparent in 2016 at the end of the second period of grazing, although the overall effects of the grazing treatments were weaker than in 2012. Collectively, these results might indicate inertia in the system, whereby the effects of applying or withdrawing grazing take a few years to manifest. The treatment effects were detected in species frequencies but not top cover (which is more of a short-term effect), which supports this premise. Some long-term grazing effects on graminoids were also noted in the restoration plots.

Invertebrates

In this study, invertebrates were counted in major taxonomic groups to provide an indication of the overall numbers of individuals associated with the grazing treatments and vegetation parameters. Pitfall trapping provides an activity-density index of epigeal invertebrates but does not sample foliar or soil-dwelling invertebrates efficiently. However, some clear relationships were detected in 2016 at the end of the second grazing period as well as in the earlier period of grazing up to 2010.

In 2016, all the invertebrate groups were more associated with acid grassland vegetation than with wetter, mire vegetation. This effect had not been detected after the first period of grazing but it is consistent with other studies that have shown relationships between upland invertebrate assemblages and plant species composition (Sanderson *et al.*, 1995; Dennis *et al.*, 1997; Littlewood *et al.*, 2006). The relationships detected here might reflect differences in productivity in the vegetation types, with grassland tending to produce more biomass in terms of both living material and litter than the bog vegetation growing on a less fertile peat substrate. However, this study did not allow comparison of the habitat preferences of functional groups or individual species, which might have revealed more subtle preferences of certain groups or species with the mire vegetation. There was also a tendency for fewer captures in shorter vegetation. This could have been due to higher numbers or rates of activity at the soil surface or simply superior trapping efficiency in shorter vegetation.

There was also an effect of grazing treatment on the invertebrate assemblages, most groups being associated less with SC than the other treatments. The overall stocking rate was greatest in SC, so the differences in invertebrate activity-density might have been attributable to higher levels of disturbance in this grazing regime. Previously in 2010, there had been a strong treatment effect on the invertebrates, with lower numbers of all groups caught where cattle were present. Similarly, this might have reflected higher levels of disturbance from the cattle compared to sheep. It was notable that most Collembola were caught in the LS treatment and least in SC. As detritivores, Collembola probably indicate a higher density of dead plant material in LS, which would result from lower levels of defoliation and disturbance.

In 2016, the treatment effects on invertebrate captures were only evident in September, which was at the end of the summer period of grazing. Similarly, in 2010 the treatment effects had been stronger in September than in July. This indicates that invertebrates respond relatively rapidly to changes in the environment and are indicative of recent management as well as variation in vegetation composition that has developed over much longer timescales.

Livestock performance

As in the previous grazing period up to 2010, cattle and sheep performance varied from year to year and was probably attributable to the amount and quality of forage available each year, and would reflect variation in weather conditions. The initial weight and condition of the animals would also affect performance each year. In 2013, the first year after the no-grazing period, cattle performance was exceptionally good, and followed the two-year period when the site was not grazed, which had allowed the biomass of available forage to build up. This was also the only year when weight gains differed between the two treatments, being slightly greater in CO than SC. This suggests the presence of sheep might have slightly the reduced the forage that was available to cattle. In contrast, the lowest gains were in 2016 when there was generally poor growth in the region following a dull summer period. Annual variation in growth rates of cattle might also depend on how well they adapt to being enclosed within a small group. Cattle used to running in a large group sometimes do not settle well and this could adversely affect their performance.

Ewes also performed very well in 2013, which could be at least partly attributable to the lack of grazing in the previous two years. Lamb performance as measured by weaning weights showed no difference among treatments in any single year. However, liveweight gains were inferior in the HS treatment in some years, suggesting an effect of sheep stocking rate on lamb performance, which has been highlighted in other studies (Merrell *et al.*, 2001). Overall, there was little evidence that cattle impaired sheep performance or vice versa, nor that there was any improvement in performance in the mixed grazing regime. The one exception to this was the superior lamb liveweight gains in the SC treatment in one year of the study, consistent with the findings of Fraser *et al.* (2013).

Overall, the livestock performance was considered by the grazier to be satisfactory from the economic perspective, given that agri-environment scheme payments were also available on this type of land. Together with the cattle results, this suggests that the improved performance after a period of no grazing could partly compensate graziers for the lack of returns during the no-grazing period of a rotational or 'pulsed' grazing system. This would however be dependent on other grazing being available during the no-grazing period on the land in question. An alternative might be to subdivide larger moors into paddocks and rotate livestock among the paddocks each year, although this would only be possible on sites where fencing was not an issue.

Heather restoration plots

The results confirm previous conclusions (Mitchell *et al.*, 2008a, b; Critchley *et al.*, 2013) that some form of disturbance and a source of *C. vulgaris* seed is essential for the establishment of *C. vulgaris* on graminoid-dominated moorlands. If *C. vulgaris* seed is not already available in the soil seed bank (or possibly in the seed rain if sparsely distributed plants are present) then it needs to be added artificially. Even 14 years after the start of the experiment the cover of *C. vulgaris* was continuing to increase, reaching over 50% cover in some plots. Previous results showed that cattle grazing or no grazing was the best grazing regime for the establishment of *C. vulgaris* (Mitchell *et al.*, 2008a, b; Critchley *et al.*, 2013) and the current results also confirm this over a longer period.

The primary aim of this work was to assess if grazing could be reintroduced after intervention treatments to re-establish *C. vulgaris* in graminoid-dominated moorland. While re-introducing grazing did not destroy all the established *C. vulgaris* it did reduce it. Changing the fencing around on half the plots showed that grazing resulted in a rapid change in *C. vulgaris* cover, such that it was the current grazing (grazed or ungrazed) in years 12-14 of the project that determined the current cover of *C. vulgaris*, not the previous pattern of grazing in years 0-10. If these results are replicated at larger spatial scales (with greater variability in vegetation, exposure and livestock movements), it is disappointing as the ultimate aim of any restoration would be to reintroduce grazing to allow for the continued economic viability of these moors. However there were differences between the grazing treatments. The introduction of cattle grazing to plots that had been disturbed (rotavated or trampled) and seeded resulted in about 40% cover of *C. vulgaris* being present compared to ungrazed plots with 50-60% cover. Thus although *C. vulgaris* cover was reduced by cattle, it is still within acceptable levels for restoration objectives. However the introduction of sheep grazing resulted in *C. vulgaris* cover dropping from about 40% cover to about 20% cover. Thus introducing the cattle-only grazing regime while continuing to maintain *C. vulgaris* cover is possible but introducing sheep grazing is more likely to be detrimental. The removal of grazing in years 10-12 showed that if *C. vulgaris* was present it would rapidly increase in cover. Thus if sheep were the desired grazer a rotational or pulsed grazing system where the area was left ungrazed for a couple of years every 10 years may allow the *C. vulgaris* to recover sufficiently to persist.

Fencing history (if the plot was fenced or unfenced in the first 10 years of the experiment) was important in explaining the cover of *N. stricta*, *F. ovina* and *J. squarrosus* but not *C. vulgaris* or *V. myrtillus*. This suggests that the dwarf shrubs respond quickly to changes in current grazing whereas previous grazing or fencing can have a lasting impact on the cover of graminoids.

Seeding with *C. vulgaris* had a significant impact on the cover of *Agrostis* sp., *J. squarrosus*, *N. stricta* and *V. myrtillus*. This is because seeding had resulted in the increased cover of *C. vulgaris* which had outcompeted these species, thus reducing their cover. The response of species such as *Agrostis* sp., *J. squarrosus* and *N. stricta* is beneficial in terms of reducing graminoid cover and restoring the typical moorland community. However, this may be less beneficial for *V. myrtillus* which is part of the desired moorland community, and also appears to be susceptible to grazing.

The restoration treatments had a significant impact on how similar the community was to a target community with 50% *C. vulgaris* cover. As in previous years of the study, seeded and disturbed plots were more similar to the target than unseeded or undisturbed plots but there was no difference between the grazing treatments in their similarity to the target. This latter effect was probably due to the two years without grazing between 2010 and 2012. Changing the fencing round did have a significant impact on how the similarity index changed from 2010 to 2016 with sub-plots that had the grazing removed (GUU) increasing in similarity to the target more than sub-plots that were previously ungrazed and had grazing added (UUG).

The Principal Response Curve analysis show that across all the different grazing regimes two community types were developing. Firstly one dominated by grasses with a range of species and little *C. vulgaris* found in undisturbed and/or unseeded subplots and second a community dominated by *C. vulgaris*, found in the seeded rotavated or trampled subplots. Introducing grazing in the ungrazed plots resulted in a move away from a *C. vulgaris* dominated community, particularly if sheep grazing was introduced.

Conclusions

1) There was evidence that competition among plant species was driving some of the longer-term changes in vegetation, and that this interacted with grazing. At the paddock scale, an overall decline in the relatively unpalatable *N. stricta* was most likely attributable to competition from other species, under the moderate grazing intensity of the treatments applied, and also when grazed ceased. Within restoration plots, there was less cover of *N. stricta* and *J. squarrosus* if the plots had not been grazed during the first 10 years of the study than if they had been grazed. In contrast, *F. ovina* cover was greater if plots had not been grazed during the initial 10 years, suggested competitive interactions among these graminoid species that was modified by selective grazing by livestock.
2) There was also evidence of similar effects among dwarf shrub species, as *V. myrtillus* was impacted by increased cover of *C. vulgaris* in the restoration plots, was grazed more than other key species at the paddock scale and impacted by grazing in the restoration plots. Seeding of *C. vulgaris* also reduced cover of grasses in the plots.
3) Grazing *per se* had a greater effect on plant species composition at the paddock scale than the individual grazing treatments. However, the cattle-only grazing regime was beneficial for *C. vulgaris* in the restoration plots over the long-term, and there was also some evidence of this at the paddock scale.
4) Cessation and re-introduction of grazing also affected plant species cover in the shorter term. At the paddock scale, dwarf shrub and forb covers declined while unpalatable graminoid cover increased when grazing was re-introduced. Similarly in the restoration plots, *C. vulgaris* cover increased on removal of grazing, and declined when it recommenced. The effect was greatest under sheep

grazing and least under cattle grazing. For both *C. vulgaris* and *V. myrtillus*, it was the current grazing that affected cover more than the long-term grazing regime.

5) Disturbance was also an important driver of the vegetation dynamics. Disturbance, in combination with seeding, was necessary for successful initial establishment of *C. vulgaris* in the restoration plots, an effect that persisted over the course of the 14-year study. In contrast, the increase in *J. effusus* seen in response to the initial disturbance in the restoration plots did not persist in the longer-term. Trampling by livestock might also have reduced bryophytes in the paddocks when grazing was re-introduced. Variation in levels of disturbance might also have been the driver responsible for the relationship between grazing regimes and invertebrates.
6) Restoration of *C. vulgaris* was most successful with seed addition and disturbance at the outset, and with no subsequent grazing, or grazing under the cattle-only regime. Without this, manipulation of grazing alone will take many years to alter plant species composition, due to slow growth rates and species turnover in relatively unproductive grass moorland where *C. vulgaris* is scarce or absent. Given successful establishment of *C. vulgaris*, 8 years of grazing following by cessation of grazing resulted in greater similarity to the target community than re-introducing grazing after 10 years without grazing.
7) Invertebrate composition was partly related to spatial variation in the vegetation composition, itself partly attributable to the prevailing environment, particularly edaphic properties. Invertebrates were also affected by the grazing regimes, and appeared to respond relatively quickly to changes in grazing. It is likely therefore that invertebrate communities will change in response to vegetation restoration in the long-term, as well as to more ephemeral effects of grazing management.
8) Performance of both cattle and sheep varied annually, probably in response to variation in weather and subsequent forage biomass and quality. However, there was also a suggestion that the two-year period without grazing had some short-term benefit in providing more, or better, forage in the following year. There was little variation in livestock performance among the grazing regimes, apart from lamb performance in some years.
9) Management of moorland habitats for multiple objectives will require certain compromises to be made. At sites similar to this one, restoration of *C. vulgaris* would ideally be done in the absence of grazing or under a similar cattle-only grazing regime. However, economic objectives will often preclude long-term cessation of grazing, and will also often require the inclusion of sheep in the grazing system. A rotational or pulsed grazing system similar to the one applied here could provide an acceptable compromise. Vegetation restoration could proceed, albeit more slowly than under the optimum management regime, and livestock production could still be viable, especially if supported by a specific payment to support such a system under an agri-environment scheme.

Future Work

1) The current project is based on a single site, which is representative of *N. stricta* moorland, a widespread type in upland Britain. Pulsed grazing systems need to be tested on other moorland sites containing a range of habitat types to test their effectiveness more widely.
2) The heather restoration experiments were carried out at a small spatial scale in order to test a range of treatments on relatively homogeneous vegetation. The most successful treatments for restoring *C. vulgaris* have been identified, but these need to be rolled out at larger spatial scales to test their application at the scale of a moorland grazing unit.
3) The Pwllpeiran site is registered as a long-term experimental site by the Ecological Continuity Trust (www.ecologicalcontinuitytrust.org). There has been considerable investment in the grazing experiment since 2002 and continuation of the grazing management would provide a unique opportunity to test the effects of different grazing regimes over a longer period of time. Maintenance of the restoration plots would also allow the long-term effects of the restoration treatments to be assessed again at some time in the future. The site also provides a valuable resource for other experiments to be carried out on a site with known grazing history, which is a scarce resource.

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Knowledge Exchange

1) A paper was presented at the AAB / BES conference 'Environmental Management on Farmland' in Brigg in April 2013:
2) A paper was presented at the Society for Ecological Restoration conference in Oulu, Finland in August 2014.
3) A paper was presented at the European Grassland Federation conference at Aberystwyth in September 2014. The study site was also included in a mid-conference field visit, which was attended by an international audience of grassland ecologists and agronomists.
4) Results of the project were included in a presentation entitled "Review of upland grazing research in relation to spatial factors", given at a Defra / NE workshop in York in October 2014. The aim of the workshop was to inform the design of research to assess agri-environment grazing options for maintaining favourable conservation status of upland habitats.
5) A paper was presented at the Agricultural Ecology Special Interest Group of the British Ecological Society at Queen's University, Belfast in April 2015
6) A visit to the field site was included for delegates at the British Grassland Society Research Conference at Aberystwyth in September 2015.
7) A meeting was held on 14 – 15 October 2015 with Natural England and IBERS staff to demonstrate the project and consider future opportunities at the site.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

Conference proceedings

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