APPENDIX 3: Development of practices via modelling

3A: Vegetation

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Appendix 3A: Vegetation

Part 1: The vegetation model

INTRODUCTION

This appendix is divided into two parts. Part 1 provides a brief description of the vegetation model and how it has been developed under this contract. Summary results of sensitivity testing of the model are also reported together with a comparison of model outputs and field data on vegetation change collected as part of the contract. In Part 2, results from the evaluation of different grazing scenarios on four moorland sites in Northumberland, Cumbria, Devon and Wales are reported, together with a discussion of key factors driving vegetation change and the potential of different livestock species for maintaining and enhancing upland heath and blanket bog.

RATIONALE FOR DEVELOPING THE VEGETATION MODEL

Upland moor is typically a mosaic of different dwarf shrub and grassland heath communities. In the absence of grazing, vegetation change within these communities is largely driven by competition between species – the outcome of which will depend on the productivity and condition of the species themselves. Grazers influence the outcome of competition by their selective foraging behaviour and by the removal of above-ground biomass that can affect plant performance. Since grazers differ in their plant preferences and in their energy requirements, the type and number of grazers and the timing of the grazing season can have profound effects on the rate and direction of vegetation change. In addition, the likelihood of a species being eaten is influenced by its palatability, its abundance and by the composition of the surrounding vegetation.

The combination of these different factors increases the variety of possible outcomes for vegetation change at any one site. In order to understand the individual and interactive roles of these different factors in driving vegetation change on upland heath, a spatially explicit vegetation model was adapted and used to explore the likely outcomes for vegetation change of a range of different grazing regimes. Specifically, the model was used to:

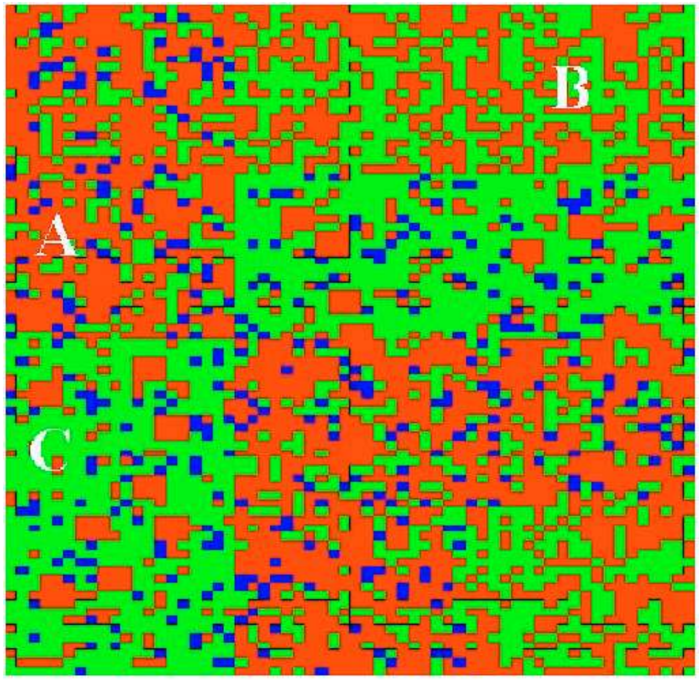
- provide insights on the factors driving vegetation change;
- enable long term predictions of vegetation change to be made for the systems study treatments,
- assess the potential of different grazing regimes to deliver environmental benefits in different upland vegetation types
- enable consideration of benefit trade-offs and to help prioritise land management options for different upland vegetation types
- enable consideration of the potential effects of recent changes in agri-environment policy on upland vegetation

THE VEGETATION MODEL

A grid-based modelling approach was used to explore the dynamics of upland vegetation change under different grazing regimes. The model was constructed hierarchically to enable simulation of upland vegetation mosaics. The basic unit of the grid is the cell, each of which is occupied by a single plant species of a known age. Cells of different plant species are grouped into tiles representing the different plant community types present in the field. 'Plant community' tiles are then distributed across the spatial grid (Figure 1) in a pattern simulating the mosaic of vegetation types sampled and mapped in the field.

Within the model, plant species change is driven by the interaction of livestock foraging behaviour, interspecific competition between plants and the spatial distribution, age and starting abundance of the different plant species present. Descriptions of early versions of the vegetation model are reported in Gardner (2002) and in Defra contract report BD1218 (Gardner *et al.,* 2001) which reports on the functions implemented within the model.

Figure 1 **An example of a simple spatial grid with 3 different species (red, blue and green) and three different tile types A, B, and C**



A total of 16 plant species/groups are included in the model. These are: *Calluna vulgaris, Carex* sp., *Deschampsia flexuosa, Empetrum nigrum, Erica tetralix, Eriophorum* sp., *Juncus squarrosus, Molinia caerulea, Nardus stricta, Scirpus cespitosus, Vaccinium myrtillus*, Broad-leaved grasses, Fine-leaved grasses, Mosses, Rushes and Bare ground. Each species/group (except Mosses and Bare ground) is described by three age states – which vary in length according to the species and in competitive vigour (see Gardner *et al.* 2001)

Within the spatial grid, each individual plant is surrounded by eight neighbours. Thus an individual plant competes with each of its eight neighbours to determine whether it will persist into the next timestep. Plant competition is modelled as a probability function with the competitive vigour of each plant species being determined by its age state, condition (grazed or ungrazed) and by the species and age states of its neighbours. Thus the probability of an individual persisting at its location is determined by the composition of its neighbourhood (the eight neighbours) and not by the interaction between a single pair of individual plants.

Within the model, the effect of grazing animals on the rate and direction of vegetation change is determined by the animal breed (size and nutritional requirements), the productivity of the vegetation (*e.g.* biomass production, digestibility in different seasons), the foraging behaviour of the animals (*e.g.* feeding preference, ability to access different vegetation types) and the grazing regime (*e.g.* number of animals, mixed *vs.* single species grazing, seasonal changes). The parameters for each of these different elements are based on empirical data reported in the literature and the assumptions underlying each element are listed in Box 1.

BOX 1: Biological assumptions included in the model

1. Plant competitive vigour varies with its age and with the age stage and the species with which it is competing.

2. Change in the area occupied by each species is assumed to occur as a result of contests between neighbouring species rather than by contests between individuals of the same species.

3. Plants compete via vegetative growth and expansion into neighbouring cells. No seed dispersal is included in this model.

4. On bare ground, plants can regenerate by seed (from the seedbank) or vegetatively from neighbouring plants. Competition between seeds/seedlings is assumed to be important only on patches of bare ground among seedlings germinating from the seedbank.

5. Grazing is assumed to reduce the competitive vigour of each plant species. The size of the reduction depends on the grazing tolerance of the plant, *e.g., Nardus* is more tolerant than *Calluna,* the type of grazing livestock and on the number of times a plant is grazed within the current year.

6. The productivity of each plant species is assumed to vary with growth stage, season and geographical region. Empirical data on productivity is included in the model from Defra contract BD1203.

7. Plants are assumed to vary in digestibility both between species and between seasons. Empirical data on productivity of each species is combined with empirical data on seasonal variation in digestibility to give an estimate of the nutritive value of each plant species present in a field, measured in MJ/month

8. The effect of burning, cutting, scarifying *etc* has been assumed to involve the creation of an area of bare ground. This can be directed to any part of the simulated field *e.g.* burning can be limited to specific stands of *Calluna.* Probability of regeneration from seed is treated as a function of the management technique (*e.g.* seed regeneration is better after burning than after cutting[6]. Regeneration from vegetative regrowth depends on the age and competitive vigour of the surrounding plants.

9. Sheep are assumed to be selective foragers showing a preference for *Agrostis* and *Festuca* sp. for example, before *Nardus* and *Calluna.* Foraging preference also changes with plant age, young *Calluna* being preferred to mature or old *Calluna,* young *Molinia* being preferred to older tussock *Molinia* (where nutritive value of the plant is reduced by the accumulation of dead leaves and litter).

10. Livestock vary in their accessibility to different vegetation types. For example, sheep are assumed to lack the ability to disperse freely within mature or degenerate heather, confining their movements primarily to the edges of such stands. Cattle by contrast can move freely through tall vegetation and thus have greater access to areas of mature *Calluna* and tussocky grasses such as *Molinia* and *Nardus,* than sheep. This influences where they graze on the simulated moor.

MODEL DEVELOPMENT UNDER BD1228

The original model developed under earlier Defra contracts (Gardner *et al.* 2001, 2002) was designed to assess the effect of single animal species grazing alone (either sheep or cattle). For this contract the model has been completely re-written to enable the spatial grids used in simulation studies of individual sites to be grazed simultaneously by sheep and cattle. In re-writing the model, amendments were made to the grazing preference, animal energy requirement and stocking rate algorithms to enable the individual requirements of each animal species to be considered simultaneously during a simulation and the outcome of grazing by each animal species to be integrated into the model outputs. These algorithms were also amended to allow the stocking rates of different animal species to vary between seasons and/or for the vegetation to remain ungrazed for part of the year.

A specific revision was made to the algorithms used for simulating cattle foraging behaviour. This recognized that cattle, with their large energy requirement, tend to select vegetation on the basis of patch size (Waterhouse *pers.comm.*) rather than on the basis of individual plant species or age stage. An algorithm enabling the identification of species patches of different sizes was incorporated into the model and the grazing preference rules for cattle relaxed, particularly for grasses, such that cattle were assumed not to discriminate between different age stages of a species.

During this re-development, model outputs were refined to enable predictions to be made of species change for individual plant communities present in the spatial grid. This was considered important as earlier field experiments (Gardner *et al.* 2001) had demonstrated that the response of individual species to a particular grazing regime was strongly influenced by the plant community in which they were present.

Outputs were also adjusted to enable provision of spatial and species age structure data to be made available at different stages of the simulation for the bird modeling work (Appendix 3b).

SENSITIVITY TESTING

Sensitivity analysis has focused on assessing the effect of varying the initial competitive probabilities assigned to the different age stages of *Calluna* and *Molinia* and the duration of these age stages, on model estimates of vegetation cover. These species were chosen as they were the ones within the model (and in the field) between which competition was most likely to occur (see Gardner *et al.* 2001 and part 2 of this Appendix).

The competitive probabilities for each species and each age state were systematically increased or decreased by 0.05, 0.1 and 0.2 in turn, and the effect on *Calluna* cover recorded. In each case the change in *Calluna* cover was calculated as the percentage increase or decrease in *Calluna* cover observed between Year 1 and Year 10 (*i.e.* 100(cover in year 10/cover in year 1)). Change measurements were based on *Calluna* cover at Year 1 rather than at Year O since species composition in the model undergoes a settling phase during this initial period and inclusion of these data could distort the interpretation of the species response

Model estimates of vegetation cover were reasonably robust to variation in the initial competitive probabilities of young *Calluna*, young and mature *Molinia.* This outcome reflects the nature of the competitive function used in the model. Competition between species is influenced by the species composition of the neighbourhood surrounding each plant. This neighbourhood modifies the initial competitive probability assigned to the age stages of each species. Since species composition varies widely between neighbourhoods, the actual competitive probability associated with any one species will also vary widely across the spatial grid. The outcome of species competition is thus likely to be more strongly influenced by variation in the neighbourhood of species surrounding each plant rather than by the initial competitive probability assigned to each species.

Sensitivity analysis did indicate, however, that a reduction in the initial competitive probability of mature *Calluna* could have a significant effect on model estimates of *Calluna* cover. This suggests that for factors such as grazing that may impact significantly on the competitive vigour of mature heather, reliable data will be needed to quantify and understand the nature of their impact in order for the effect to be modelled accurately.

Sensitivity analysis was also undertaken on the duration of the different growth phases of *Calluna* and *Molinia.* Shortening the duration of the young *Calluna* growth phase from 5 to 2 years, resulted in a significant increase in the cover of *Calluna* compared to the standard life-cycle duration (control) used in the model. Early maturation of *Calluna* (*i.e.* faster aging of all *Calluna* growth phases as might occur under climate change) led to a faster rate of increase in *Calluna* cover compared to the control scenario, but the final percentage cover of *Calluna* was similar for both scenarios. Varying the duration of *Molinia* growth phases had little overall effect on the cover of each species compared to the control scenario. These results indicate that factors that reduce the duration of the young *Calluna* growth phase may enhance the rate of increase of *Calluna* cover. Such factors may, for example, include encouraging regeneration of *Calluna* from shoots rather than from seed.

COMPARISON OF MODEL OUTPUTS AND FIELD DATA

Three datasets were used for the comparison of model outputs with field data on species change. These were:

a) top cover data from the systems study site at Pwllpeiran collected during this contract

b) top cover data from a 10-year year study at Redesdale monitoring the effects of ESA stocking prescriptions (Defra contract BD0101, 0106, 1218)

c) top cover and frequency data from the systems study site at Redesdale collected during this contract

The results are presented as visual comparisons of field and model data as the timescales for datasets a) and c) are short and the methods used for measuring species abundance differ between the field and the model.

Species abundance is measured in the model as percentage occupancy. This is a count of the total number of cells occupied by a species within the whole spatial grid or within a set of tiles representing a plant community. Since the total number of cells available within a grid or community is known, occupancy can be given as an absolute count of the cells occupied by each species. Counts are expressed as percentages to enable comparison of species abundance between grids and/or communities of different size.

In the three field datasets, species abundance was measured as a percentage top cover or as a frequency of occurrence within 100 equal-sized cells of a 1m^2 quadrat. Top cover estimates tend to favour tall plants, which are not necessarily those that are most abundant, and low growing species or those still at a young stage may be under-represented. Frequency measurements are similar to those used in the model except that for the latter only one species can occupy a cell. In the field, several species can occur in a single cell.

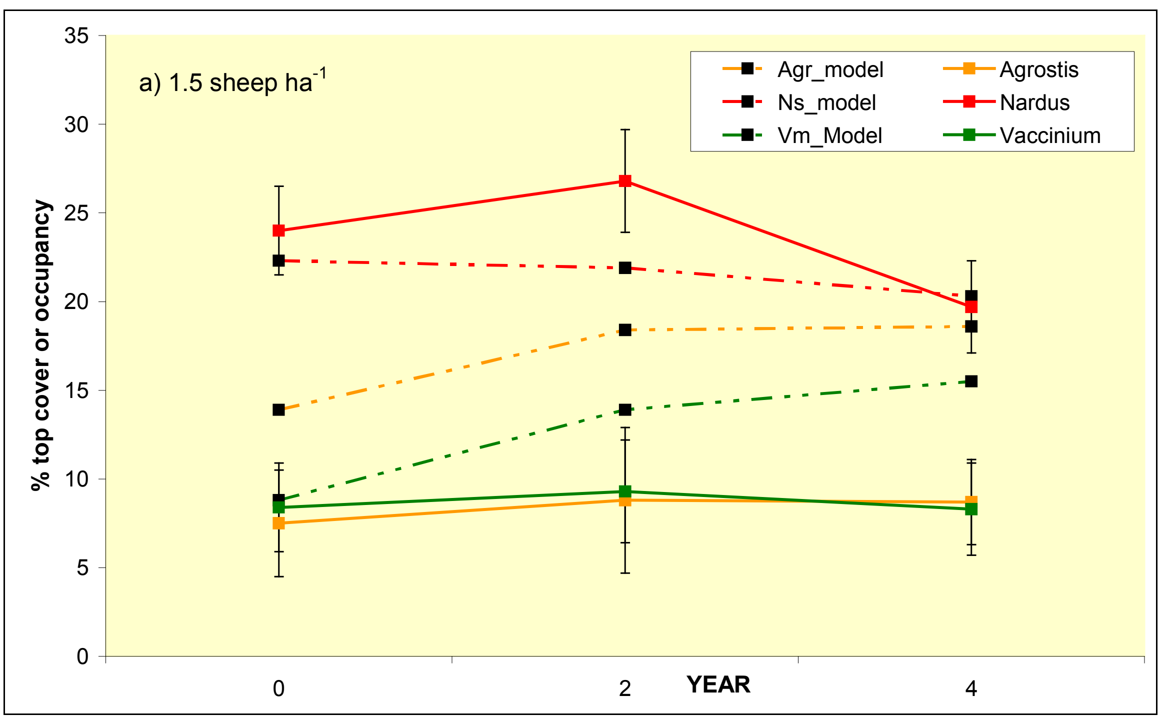
Pwllpeiran field data

Comparisons of model outputs with the mean top cover of *Agrostis, Nardus* and *Vaccinium* taken from each of the grazing treatments are given in Figure 2. Field data are the overall mean results from three replicate plots of each grazing treatment (see Appendix 4a.1 for details). Model data are the outputs from simulations of each grazing treatment undertaken on one of the site plots; the same plot was used for each simulation.

No differences were observed in the field between different grazing treatments on *Nardus* top cover (Appendix 4a.1). *Nardus* cover declined across all treatments during the 5 year study. For the same time period, model outputs indicated that *Nardus* would decline under sheep (particularly the low grazing treatment of 1.0 sheep ha^{-1}) and be maintained under cattle (Figure 2). The long-term prediction (discussed further in Appendix 3a part 2) was for *Nardus* to decline under both low sheep and summer cattle; the decline being greater under low sheep grazing.

In the field study, *Agrostis* showed a small overall increase over time but no significant differences between the sheep and cattle grazing treatments. For the same time period, model outputs indicated that Broad-leaved grasses (primarily *Agrostis* sp.) would increase under sheep and be maintained under cattle (Figure 2). The long-term prediction (discussed further in Appendix 3a part 2) was for Broad-leaved grasses to increase under sheep and to decline under summer cattle (see Table 4 in Part 2).

Figure 2 Field vs. Model data for the four grazing treatments at ADAS Pwllpeiran 2002-2006. a)1.5 sheep ha^{-1} (10 months yr^{-1}), b) 1.0 sheep ha^{-1} (10 months yr^{-1}), c) a) 1.5 sheep (10 months) + 0.5 cattle ha^{-1} (2 months yr^{-1}) and d) 0.5 cattle ha^{-1} (2 months yr^{-1})



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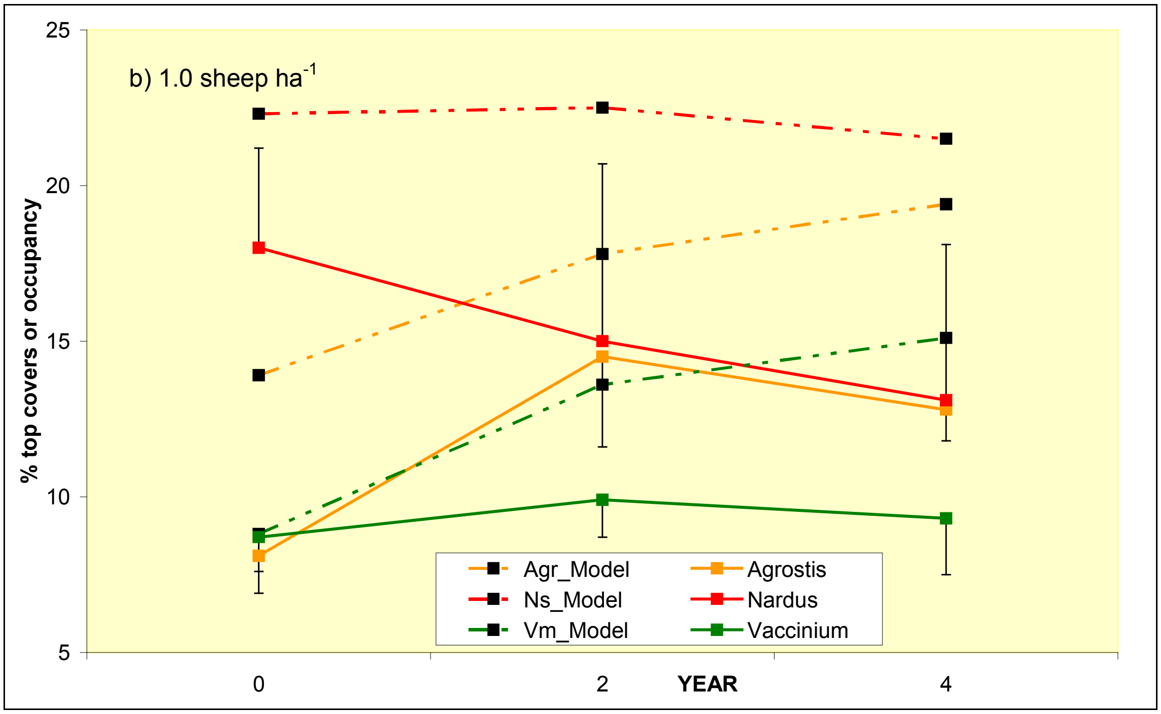

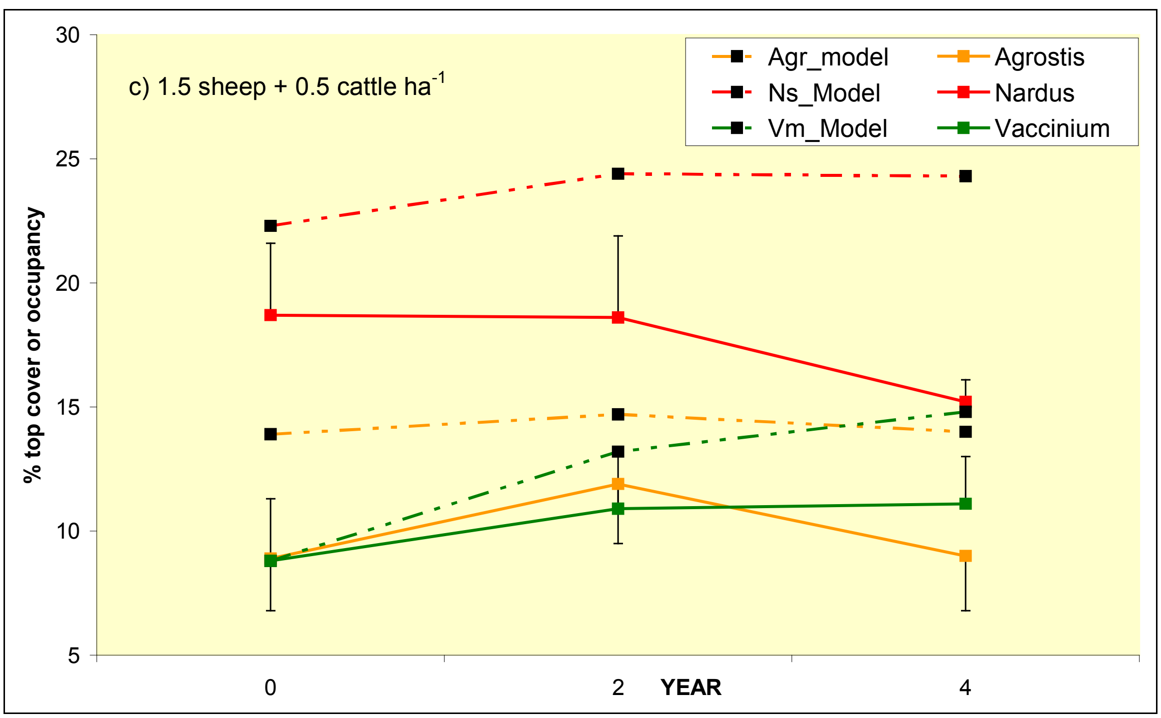

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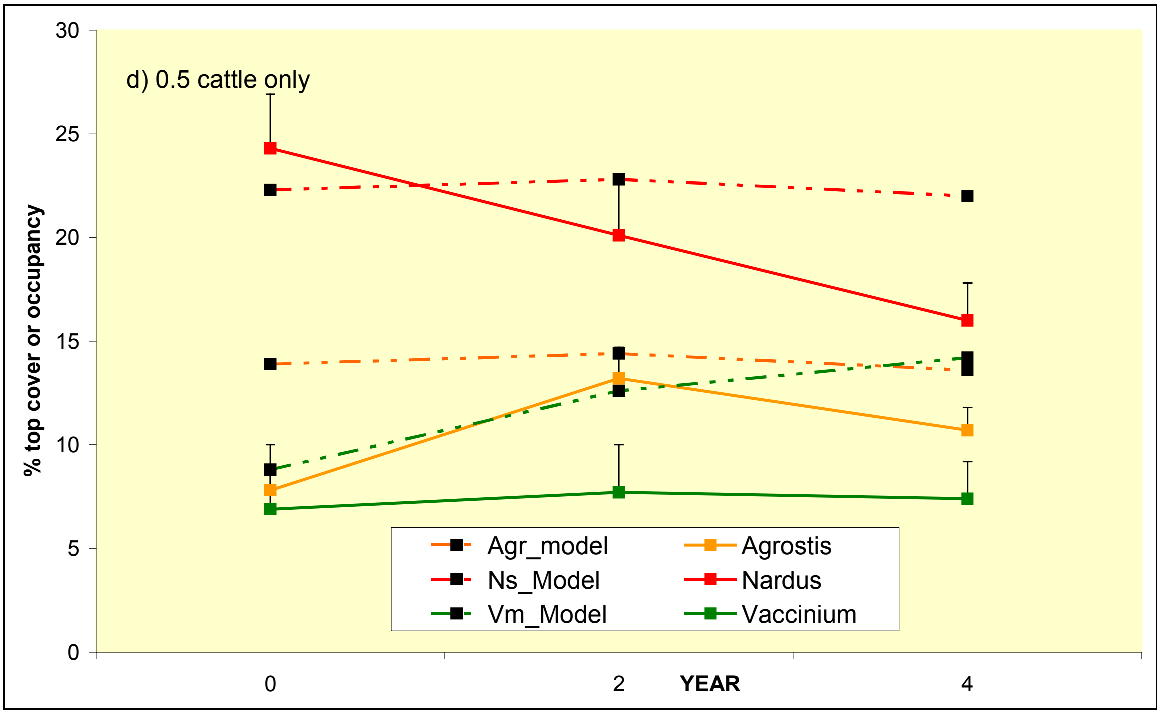


Vaccinium top cover tended to show a small increase in each of the field grazing treatments but no differences were observed between treatments. Model outputs also predicted an increase in *Vaccinium* across all treatments over the same time period although the rate of increase tended to be greater than that observed in the field.

In conclusion results for *Nardus* and *Vaccinium* appear to show reasonable agreement between the field and model data, particularly given the short-term nature of the field data and variability attached to some of the estimates of top cover. There is some discrepancy between field results and model predictions for *Agrostis* / Broad-leaved grasses but the significance of this is difficult to determine; particularly as the model outputs suggest that the difference between treatments may only emerge after 7-10 years of summer cattle grazing.

Redesdale ESA data 1990-2000

Model outputs were compared with top cover data on species change collected from the ESA Tier 1 grazing prescription (1.5 ewes ha^{-1}) applied to a 50ha paddocks on the Ashtrees heft at ADAS Redesdale (Gardner *et al.* 2001) This treatment was applied from 1990-2000 and was the longest dataset available for the site. The model outputs corresponded well with the field data for *Calluna, Molinia* and *Nardus* (Figure 3a) and for Rushes, Fine-leaved grasses, Broad-leaved grasses and *Carex* sp. (Figure 3b)

Figure 3a) Species change (*Calluna, Molinia* and *Nardus*) observed in the field (% top cover) and predicted by the model (% occupancy) for the Ashtrees heft at Redesdale stocked at 1.5 sheep ha^{-1} during 1990-2000

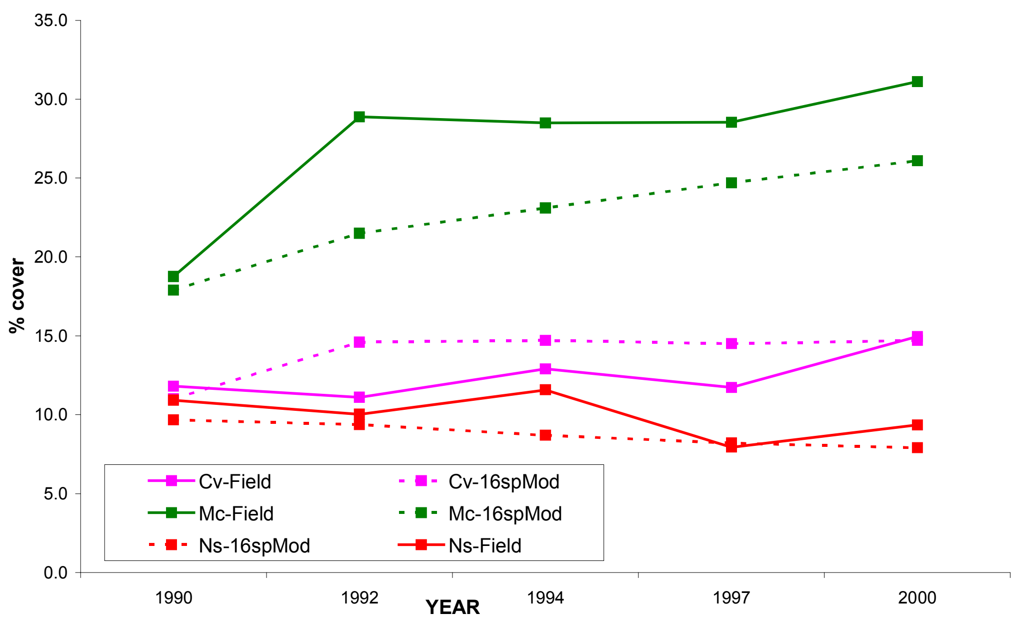
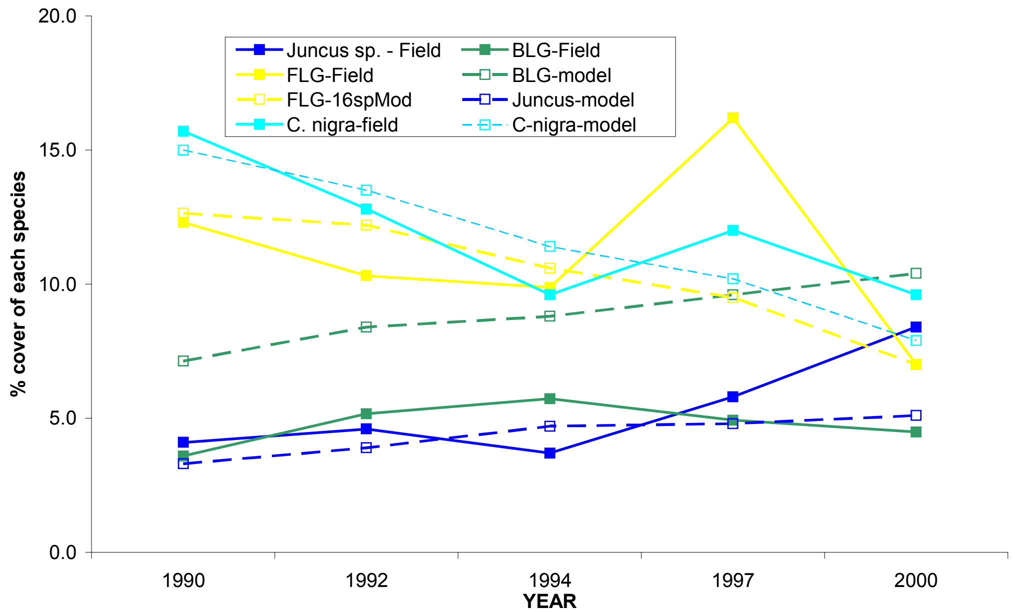


Figure 3b) Species change (*Juncus* sp., *Carex nigra,* Broad- and Fine-leaved grasses) observed in the field (% top cover) and predicted by the model (% occupancy) for the Ashtrees heft at Redesdale stocked at 1.5 sheep ha^{-1} during 1990-2000



Redesdale systems study field data

Comparisons of model outputs with the mean top cover of *Calluna* and *Molinia* taken from each of the grazing treatments undertaken as part of this contract at Redesdale are given in Figure 4. For the Redesdale systems study, four grazing treatments (High sheep 1.5 ewes ha^{-1}, Low sheep 0.66ewes ha^{-1}, High sheep 1.5 ewes + cattle 0.75 cows ha^{-1}, Low sheep 0.66ewes + cattle 0.75 cows ha^{-1}) were established in four large paddocks (Appendix 4a.2) and a separate simulation undertaken for each paddock. Both field and simulation studies examined species change at both the whole moor and plant community scale and both result sets are compared in Figures 4 and 5 below.

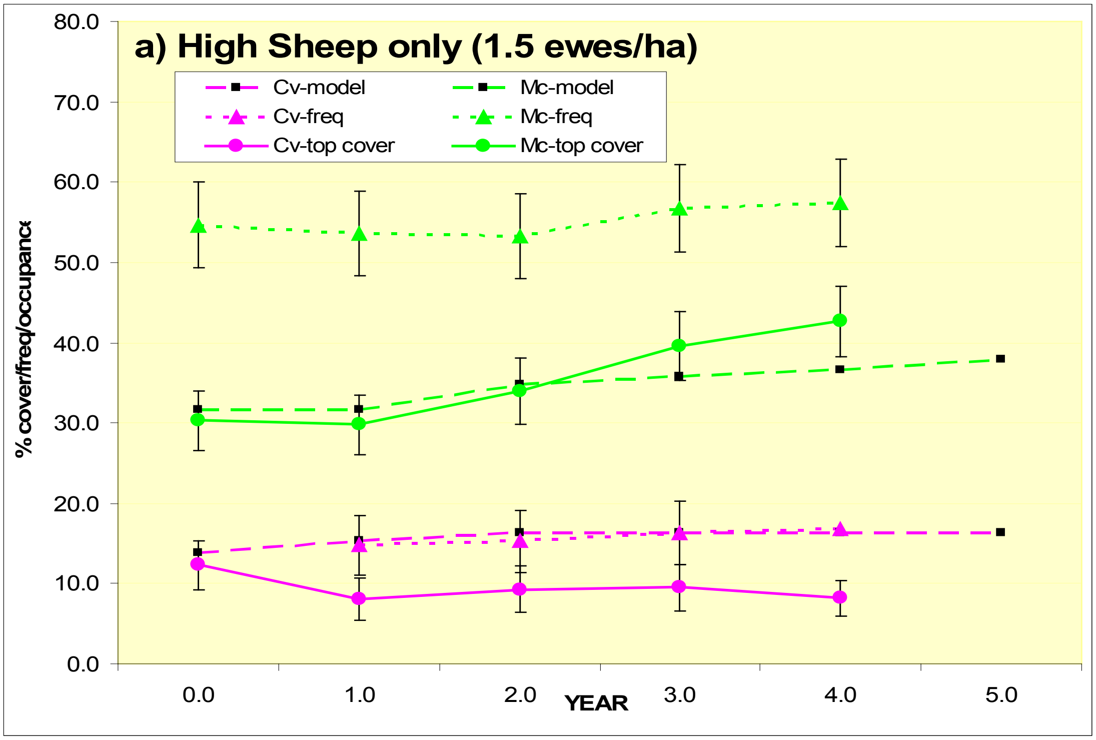
Field results indicated an increase in *Molinia* frequency and cover under sheep only grazing and a decline in frequency and cover under both mixed grazing treatments (Appendix 4a.2). In the mixed grazing treatments, the decline in *Molinia* was confined to the *Molinia*-dominated and mixed heath communities. A similar result was predicted by the simulation model, with the decline predicted as being due to decreases in *Molinia* occupancy in the *Molinia*-dominated and mixed heath communities and the rate of decline being closer to that associated with the field data on *Molinia* frequency (Figures 4 and 5).

In the field, *Calluna* cover and frequency declined in the Low Sheep and Cattle and the High Sheep and Cattle treatments respectively. This decline was attributed to cattle trampling older plants rather than grazing (Appendix 4a.2). Model outputs predicted that *Calluna* occupancy would increase under mixed grazing as competition with *Molinia* is reduced by cattle (see Appendix 3a Part 2). Cattle trampling is not included in the model due to a lack of available quantitative or probabilistic field data. This would explain the divergence between field and model results for *Calluna* seen in Figures 4c) and d) and for the Mixed Heath community in Figure 5d).

Calluna cover also declined under the High Sheep (1.5 ewes ha^{-1}) treatment in the *Calluna*-dominated and mixed heath communities. The model also predicted a decline in *Calluna* in the *Calluna*-dominated community but a slight increase in Mixed Heath. Both the short and the long-term predictions for this treatment were for *Calluna* occupancy to be maintained around its starting figure. Such a result would be expected from the results of previous work at Redesdale using a Tier 1 ESA prescription of 1.5 ewes ha^{-1}.

Under the Low Sheep treatment (0.66 ewes ha^{-1}) *Calluna* frequency was observed to increase (after 2003); a result which was also supported by the model particularly in the *Carex*-dominated and Mixed Heath communities. For the latter, the rate of increase was similar to that observed for *Callluna* frequency in the field (Figure 5c).

Figure 4 **Field *vs.* Model data for the four grazing treatments at ADAS Redesdale 2002-2006 collected at the Whole moor scale. Treatments are: a) High sheep only (1.5 ewes ha^{-1}), b) Low sheep only (0.66 ewes ha^{-1}), c) Low sheep + summer cattle (0.66 ewes + 0.75 cows ha^{-1}), d) High sheep + cattle (1.5 ewes + 0.75 cows ha^{-1}).**



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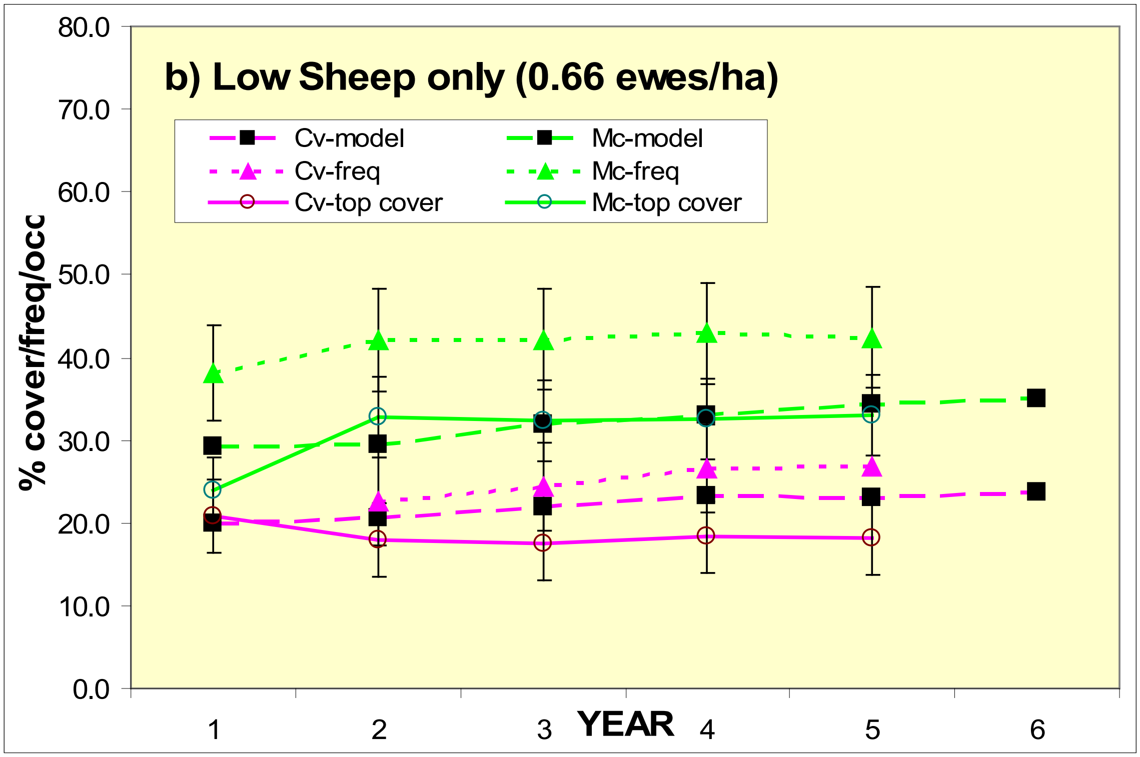

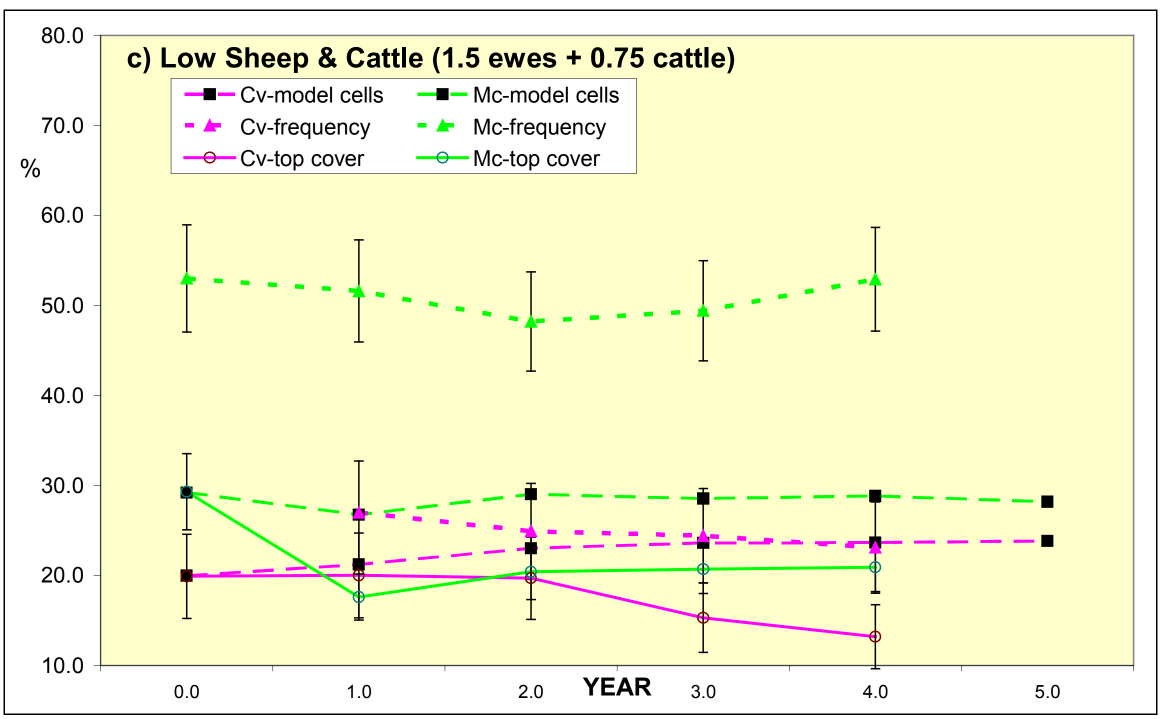

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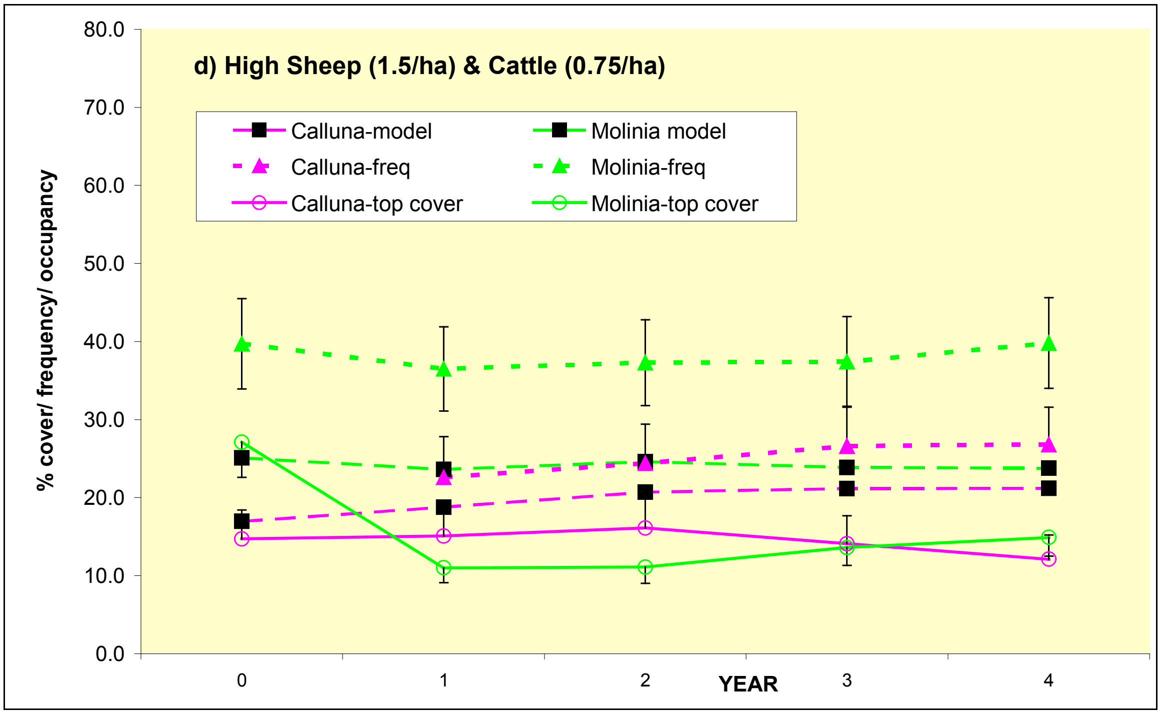
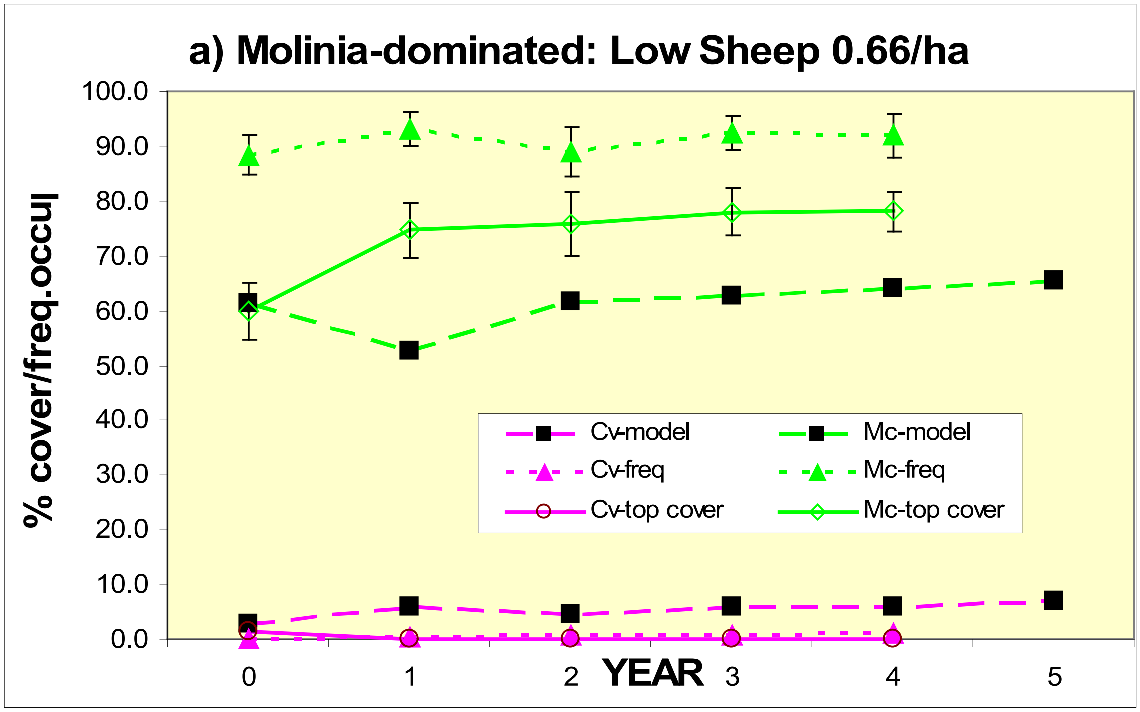
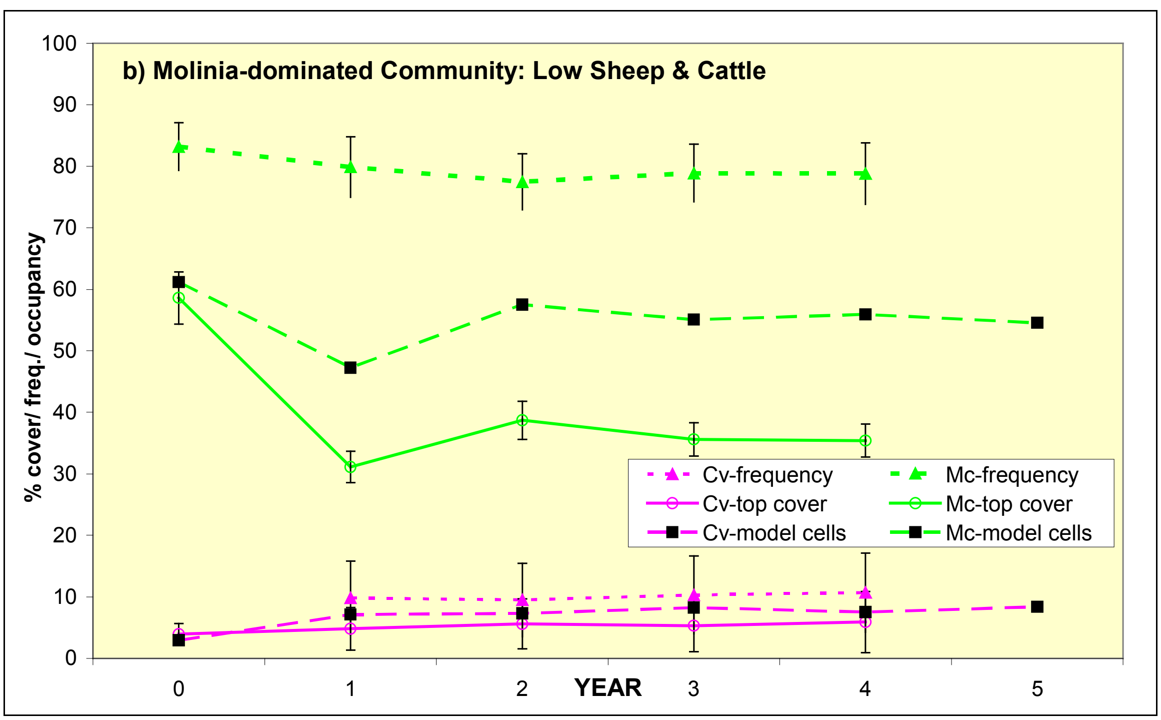


Figure 5 **Field *vs.* Model data for the *Molinia*-dominated community a) and b) and for the Mixed Heath community c) and d), under Low sheep only (0.66 ewes ha^{-1}) – a) and c),and Low sheep + summer cattle (0.66 ewes + 0.75 cows ha^{-1}) – b) and d) at ADAS Redesdale 2002-2006.**





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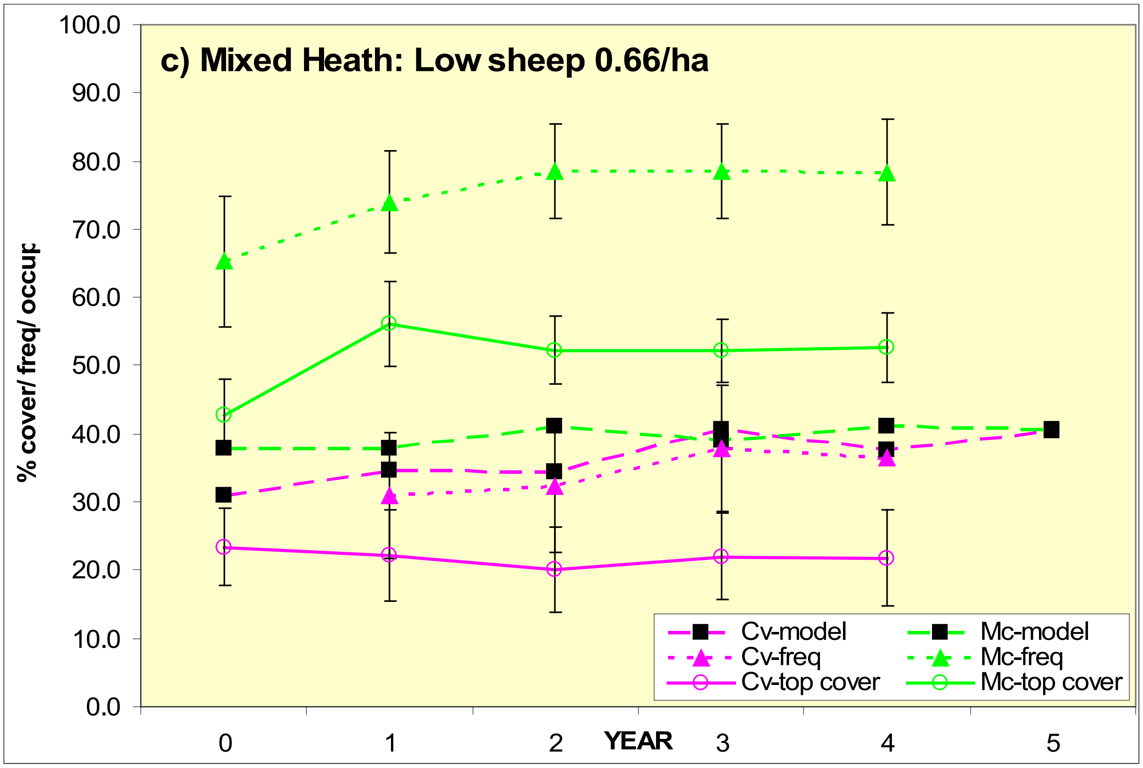
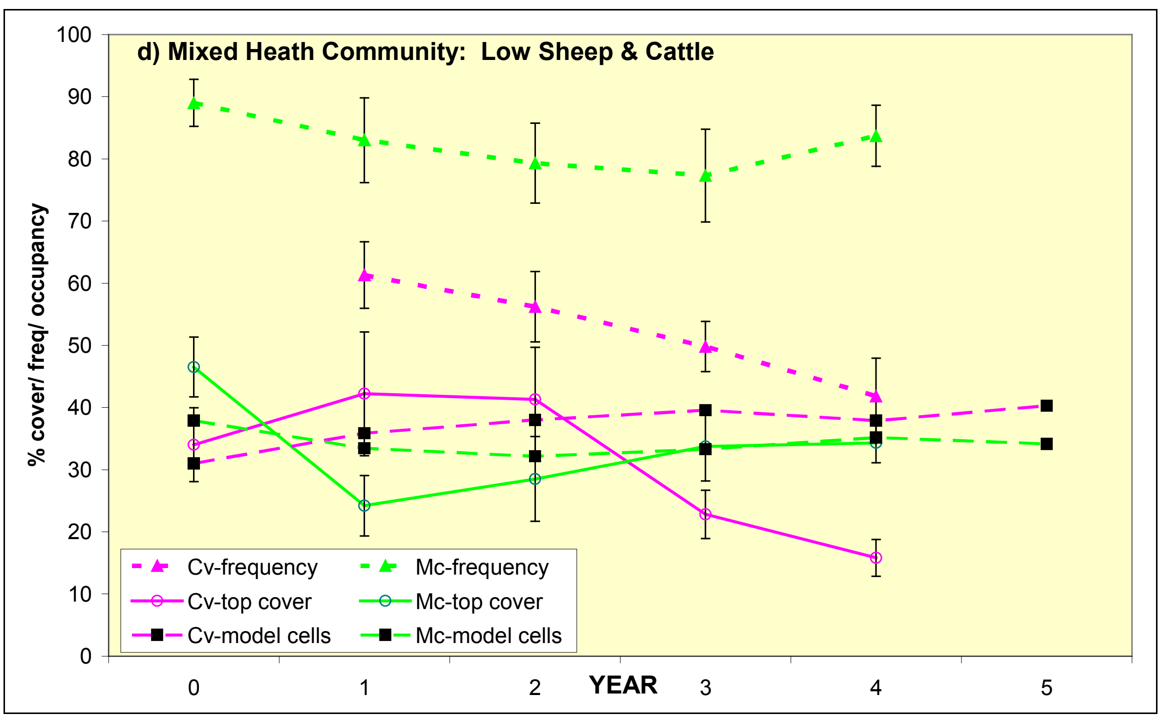




CONCLUSIONS

The vegetation model used in this study focuses on the role of species competition and species spatial distribution and the modification of these by grazers, as the key processes driving vegetation change. The model is robust to changes in the competitive probabilities assigned to individual species, reflecting the importance of spatial context (*i.e.* the local neighbourhood of surrounding plant species) in determining the actual competitiveness of each plant.

Results from the three comparative studies suggest that model outputs are largely in line with the rate, scale and direction of change observed in the field data, giving us confidence that reliance can be placed on its predictions for other grazing scenarios or sites where few long-term monitoring data are available. Local site-based factors – *e.g.* seedbank composition (Pwllpeiran) and cattle movements across a site (Redesdale), and one-off events such as heather beetle and summer drought, still have the potential to disrupt species change dynamics emphasizing the need for robust quantitative vegetation monitoring at appropriate time intervals by site managers.

Due to differences in the way vegetation extent is measured in the model (compared to field measurements) and its 2-dimensional design, its outputs can only be used as an indicator of the actual amount of each species likely to occur under different grazing treatments. Nevertheless model outputs on the rate, direction and magnitude of change should assist land managers and policymakers in their assessment of the effectiveness of different grazing regimes for delivering vegetation management objectives and the appropriateness of applying particular regimes to individual sites. Long-term predictions on the effects of the different systems study treatments and other grazing regimes are evaluated and discussed in Part 2.

Appendix 3A: Vegetation

Part 2: Development of grazing scenarios and assessment of their impact on upland vegetation change

INTRODUCTION

This work was undertaken as part of Objective 3, and had as its specific aim the evaluation of the potential of different livestock species and grazing regimes for managing key species of importance in the dynamics of upland vegetation change. These species included *Calluna vulgaris, Molinia caerulea, Nardus stricta,* Rushes *(Juncus* sp.) and Broad-leaved grasses (mainly *Agrostis* sp.). An additional aim was to provide insights on the effect of grazing on the interactions between species for sites contrasting in vegetation composition and spatial heterogeneity.

METHODS

Study sites and management objectives

Four contrasting sites were used for modelling: Birkbeck Common in Cumbria, Molland Moor in Exmoor National Park and an area from each of the two systems study sites at ADAS Redesdale in the Northumberland National Park and ADAS Pwllpeiran in the Cambrian Mountains ESA in mid-Wales. Brief descriptions of each site are given in Table 1. Each site differed in the vegetation types present (Table 1) and in its management objectives. The principal objectives for Redesdale and Molland were to reduce the extent of *Molinia,* maintain or reduce the extent of rushes (Redesdale) and to enhance the extent and condition of dwarf shrubs and the mosaic of wet heath communities. At Pwllpeiran and Birkbeck Common, the main objectives were to reduce the abundance of *Nardus,* restore the extent and condition of dwarf shrubs, reduce overgrazing (Birkbeck) and enhance the diversity of plant species present (Pwllpeiran).

Table 1 Descriptions of the four study sites

Study Site	Site Description
Redesdale, Northumberland	The site sits within the Northumberland National Park and comprises 103 ha of degraded *Calluna-Molinia* wet heath. The site formed one of the systems studies for this study, and prior to this had been split into two paddocks and grazed by Scottish Blackface sheep at 1.5 and 2.1 ewes ha^{-1} from 1990-1994 and at 1.5 and 0.66 ewes ha^{-1} from 1995-2002. Six communities were identified on the site (see analysis in Appendix 4a) and included *Calluna-, Molinia-, Carex nigra-, Nardus-* and *Juncus*-dominated communities and Mixed Heath (*Calluna*& *Molinia* co-dominant).
Molland Moor, Devon	The site covers an area of 681 ha of *Molinia-Calluna* mixed heath vegetation. It occurs within the Exmoor National Park and is part of a privately owned estate. Molland is also within the South Exmoor SSSI and the Exmoor Heaths SAC and was one of four regional demonstration sites established by the Heather Trust (Defra contract BD1237). Several vegetation types were identified on the site by Jerram (2000); including *Scirpus cespitosus-Erica tetralix* wet heath, *Calluna vulgaris-Vaccinium myrtillis* heath, patches of *Pteridium aquilinum, Festuca ovina-Agrostis capillaris* grassland and *Carex echinata-Sphagnum recurvum/auriculatum* mire. Past burning has influenced the balance of *Molinia* and *Calluna* present (PAA 2004). For this modelling study, habitat mapping and floristic composition data collected by PAA in 2003 were used. These included data from former and recent burned areas, mature *Calluna*, *Molinia*-dominated wet heath and mixed *Calluna-Molinia* moorland.
ADAS Pwllpeiran, Ceredigion, Wales	Also used for one of the systems studies (Appendix 4a), this site comprises 72 ha of *Nardus-Agrostis* grassland. From 1995-2002, the site had been split into two paddocks and grazed by Welsh Mountain sheep at 1.5 and 1.0 sheep ha^{-1}. The vegetation is dominated by *Nardus* and *Agrostis* sp. with *Vaccinium myrtillus* as the most frequent dwarf shrub species present (8.8%). Three communities were identified: *Eriophorum-, Nardus* and *Carex*-dominated vegetation
Birkbeck Common, Cumbria	Birkbeck Common is situated within the Lake District Environmentally Sensitive Area and covers an area of 714 ha The site is a mosaic of acid grassland, dwarf shrub heath and mire habitats, the latter being allocated to seven broad community types as follows: 41% Rough Acid Grassland, 13% Bent/Fescue grassland, 13% Blanket Bog, 13% Wet Heath, 8% Valley Mire, 6% Dry Heather Heath and 6% Rush-pasture and Rank grassland (RDS 2003). Data on the spatial distribution of community types were taken from a site survey undertaken by the Rural Development Service in 2003. This used a systematic sampling approach to map the vegetation on 250m grid across the site (RDS 2003).Since detailed floristic data were not available, an additional floristic survey was completed by Penny Anderson Associates in November 2005. 42 quadrats were sampled and data used to characterize the seven community types in terms of the overall mean cover of each of the 16 species/species groups used in the model.

Data sources and inputs to the model

For each site, the composition and spatial distribution of the vegetation was characterised from field survey data and entered into the model. For the two systems study sites at Redesdale and Pwllpeiran, vegetation data from the respective 2001 and 2002 baseline surveys and subsequent community analyses (see description in Appendix 4a) were used to initiate the model. For Molland Moor, baseline data were taken from survey and monitoring work undertaken by Penny Anderson Associates in 2003 under Defra contract BD1237. (2003). For Birkbeck Common, vegetation mapping and plant community identification data were taken from the *Vegetation Change Assessment Survey* undertaken by the National Grazing Management Team of the Rural Development Service (now part of Natural England) in May 2003, with additional species composition data collected by Penny Anderson Associates in November 2005.

Stock management inputs for Redesdale and Pwllpeiran used livestock data from the two systems studies reported in Appendix 4. A baseline grazing scenario of 2.1 ewes ha^{-1} was used for Redesdale, which was the stocking rate in place prior to the implementation of ESA stocking prescriptions in 1989. For Pwllpeiran, a baseline regime of 1.5 sheep ha^{-1} was used. This was the Tier 1 Cambrian Mountains ESA prescription in place for 7 years prior to the start of the study (Gardner *et al.* 2002**)**. For Birkbeck Common and following discussions with RDS, stocking data collected by the Rural Development Service (Chesterton *pers.comm*) in the year 2000 were used as the baseline scenario. For cattle, a maximum monthly rate of 0.048 cows ha^{-1} was used and model inputs for the daily nutritional requirements of cows varied to allow for within-year variation in cattle numbers. Cattle were present from 1 February-31 May and from 1 November-31 December. The sheep stocking rate was set at 2.84 ewes ha^{-1} and model inputs for sheep daily nutritional requirements adjusted to reflect a major reduction of sheep numbers on the site during November-April and the addition of hoggs and lambs during April-October and May-August respectively. Ponies also graze the Birkbeck site and so for the baseline regime, a stocking rate of 0.06 ponies ha^{-1} was set, with daily nutritional requirements adjusted for June and July when pony numbers on the site were reduced. Since little quantitative information on moorland pony grazing preferences and nutritional requirements is available currently, ponies were treated in the model as small dry cows (two-thirds of a dry cow applied to the site). Ponies were included in the scenarios and in the baseline regime where their daily nutritional requirements were combined with those for cattle.

Molland is grazed mainly by ponies and deer with sheep and cattle present in mid-late summer. Stocking data for Molland were provided by Simon Thorpe of the Heather Trust. Here a baseline rate of 0.63 sheep ha^{-1} and 0.147 cows ha^{-1} was used with animal nutritional requirements scaled back accordingly for months when fewer stock were present. Both deer and ponies were included in the baseline scenario but not in the standard set of sheep and cattle modelling scenarios. Both species were treated as small dry cows (two-thirds of a dry cow) in the model in terms of their daily energy requirements. With respect to grazing preferences, deer were considered to be more selective grazers like sheep and ponies to be larger 'patch' scale grazers like cows. This is an over-simplification of deer and pony grazing behaviour but reflects a lack of available quantitative data on their grazing preferences and nutritional requirements.

Development of grazing scenarios

A standard set of grazing scenarios was developed by the Consortium in consultation with the Project Steering Group (Table 2). The full set of scenarios was run at Redesdale and Pwllpeiran and a subset at Molland Moor and Birkbeck Common (Table 3). Two additional scenarios using 0.66 sheep and 0.06 ponies ha^{-1} or 0.75 cows and 0.06 ponies ha^{-1} were also run at Birkbeck Common.

Table 2 Regimes used in simulation studies of the effects of grazing on vegetation change at the four Study Sites

Regime	Period (months)	Annual frequency	Ewes/ha	Cattle/ha	Other
1. All Year Sheep					
a) High stocking	12	annual	2.1	0	25% of ewes removed in winter
b) ESA stocking	12	annual	1.5	0	25% of ewes removed in winter
c) Low stocking	12	annual	0.66	0	25% of ewes removed in winter
2. No grazing (B)	12	annual	0	0	
3. Summer sheep only					
a) High stocking	4	annual	2.1	0	May-August inclusive
b) Low stocking	4	annual	0.66	0	May-August inclusive
4. Summer cattle only					
a) High stocking	2	annual	0	0.75	July-August inclusive
b) Low stocking	2	annual	0	0.225	July-August inclusive
5. Mixed grazing					
a) all year low sheep & summer only high cattle	12 & 2 mths	annual	0.66	0.75	Cattle in July & August only
b) all year low sheep & summer only low cattle	12 & 2 mths	annual	0.66	0.225	Cattle in July & August only
c) all year ESA sheep & summer only high cattle	12 & 2 mths	annual	1.5	0.75	Cattle in July & August only
6. Rotational Grazing					
a) short rotation - all year high sheep stocking	12	2 years on, 3 years off	2.1		25% of ewes removed in winter when grazed
b) short rotation - summer only high cattle	2	2 years on, 3 years off	0.75		Cattle in July & August only
c) long rotation - all year high sheep stocking	12	1 year on, 4 years off	2.1		25% of ewes removed in winter when grazed
d) long rotation - summer only high cattle	2	1 year on, 4 years off	0.75		Cattle in July & August only

Simulation approach

A separate spatial grid was established for each site and a set of tiles created to represent the different vegetation communities present on the site. Only 16 vegetation categories were available in the model so field species data were assigned to the closest category. Consequently the vegetation categories present in the model are only approximate representations of plant species abundance in the field. Each plant within each vegetation category was also randomly assigned to one of three age categories at the start of the simulation. The age range encompassed by each of these age categories varied between the 16 different vegetation categories.

Tiles were grouped and distributed within the spatial grid in a manner following the map of vegetation types obtained from the site survey data (Table 2). The spatial grid created for a site was then used as the template for simulating the different grazing scenarios run for that site (Table 3). Livestock nutritional requirements, grazing preferences, numbers and season of grazing (time on field) were adjusted for each scenario (Table 2) and for the species and breed of stock used at the site. These adjustments were provided by the bio-economics model from SAC (Waterhouse, *pers.comm.*).

Table 3 Scenarios simulated at each study site

Grazing scenarios (details in Table 2)	**Redesdale**	**Molland Moor**	**Pwllpeiran**	**Birkbeck Common**
Site baseline regime	1a	✔	1b	✔
1. **All year sheep**				
a) High stocking	✔	---	---	---
b) ESA stocking	✔	✔	✔	✔
c) Low stocking	✔	✔	✔	✔
2. No grazing	✔	✔	✔	✔
3. Summer sheep only				
a) High stocking	✔	---	✔	---
b) Low stocking	✔	---	✔	---
4. Summer cattle only				
a) High stocking	✔	✔	✔	✔
b) Low stocking	✔	✔	✔	✔
5. Mixed grazing				
a) all year low sheep and summer only high cattle	✔	✔	✔	✔
b) all year low sheep and summer only low cattle	✔	---	✔	sheep + ponies
b) all year ESA sheep and summer only high cattle	✔	---	✔	Cattle + ponies
6. Rotational grazing				
a) short rotation: high sheep @ 2 in 5yr	✔	---	✔	---
b) short rotation: high cattle @ 2 in 5yr	✔	---	✔	---
c) long rotation: high sheep @ 1 in 5yr	✔	---	✔	---
d) long rotation: high cattle @ 1 in 5yr	✔	---	✔	✔

Simulations of each site-scenario combination were run for 20 cycles (equivalent to 20 years) and the effect of each scenario was assessed from predictions of change in percentage species occupancy. Percentage occupancy is a count of the proportion of total cells available in the spatial grid or in a set of community tiles that are occupied by a particular plant species. Within the model, an individual cell can only be occupied by one species at any one time. Predictions of change in species occupancy were available for all 16 species/species groups, but focused on those that were dominant or frequent within the communities present on a site. Assessments of change in species occupancy were calculated for the whole site and for individual communities. Since species are not evenly distributed among all the communities present, Whole Moor assessments can be a poor indicator of scenario effects as changes predicted for areas where a species is dominant, can be obscured or cancelled out by a lack of change in areas where the species is infrequent or absent. Consequently when averaged across the whole moor, overall change in occupancy for the species may seem small, even though marked changes are predicted for areas where it is dominant.

RESULTS

Calluna-Molinia wet heath

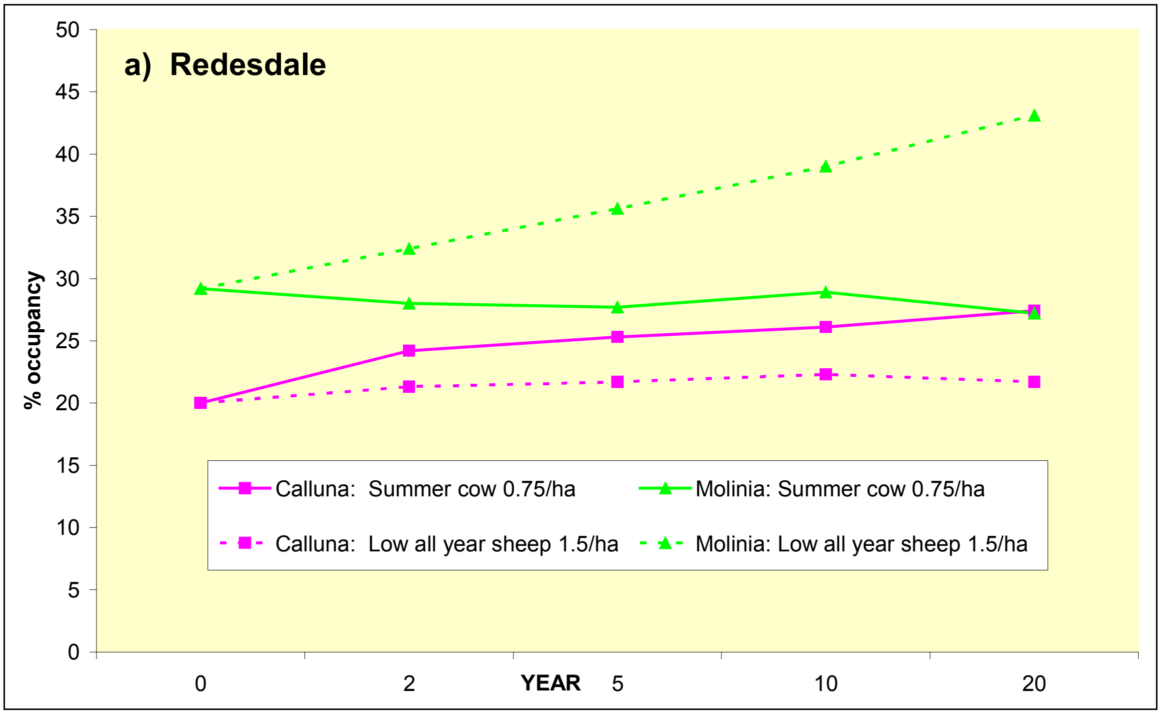
Effect of different grazing scenarios at the whole moor scale

Of the 15 scenarios run for the Redesdale site, summer grazing with cattle (Regime 4a in Table 4) and mixed grazing (Regimes 5a & 5c in Table 4) were predicted to be the best regimes for achieving the vegetation management objectives. Under these regimes the percentage occupancy of *Molinia* was predicted to be maintained or slightly reduced at the Whole Moor Scale and the percentage occupancy of *Calluna* was predicted to increase steadily. The overall effect of these predicted changes was a slow convergence in the percentage occupancy of these two species over a 20 year simulation (Figure 6a). These results contrasted strongly with the change in *Molinia* and *Calluna* cell occupancy predicted for sheep only grazing (Regimes 1a, 1b, 1c, 3a & 3b in Table 4). For these regimes, a marked and steady increase in *Molinia* cell occupancy was predicted over the 20 year period, whilst overall *Calluna* cell occupancy was maintained or slightly reduced (Figure 6a). Species change under all 15 grazing regimes is summarised in Table 4

At Molland Moor, dwarf shrub (*Calluna* and *Vaccinium*) occupancy was predicted to decline and *Molinia* to increase markedly under the baseline scenario of sheep, deer, cattle and pony grazing (Table 4). As at Redesdale, summer cattle and mixed grazing (Regimes 4a, 4b & 5a) were predicted as being the most effective in limiting the increase in *Molinia* and in enhancing the occupancy of dwarf shrubs (Figure 6b). Dwarf shrubs were also enhanced under sheep only grazing (Regimes 1b, 1c) but by a smaller amount than that predicted for cattle (Table 4). Under low sheep grazing (Regimes 1b & 1c), *Molinia* occupancy was predicted to increase (Figure 6b).

Thus for these two wet heath sites, grazing by summer cattle is predicted to be beneficial in reducing the occupancy of *Molinia* and in enhancing the occupancy of dwarf shrub species. The rate of change in species occupancy was, however, predicted to be much faster at Molland Moor than at Redesdale

Figure 6 **Change in *Calluna & Molinia* occupancy under summer cattle (0.75 cows ha $^{-1}$) and all year sheep (1.5 ewes ha $^{-1}$) grazing at a) Redesdale and b) Molland Moor**



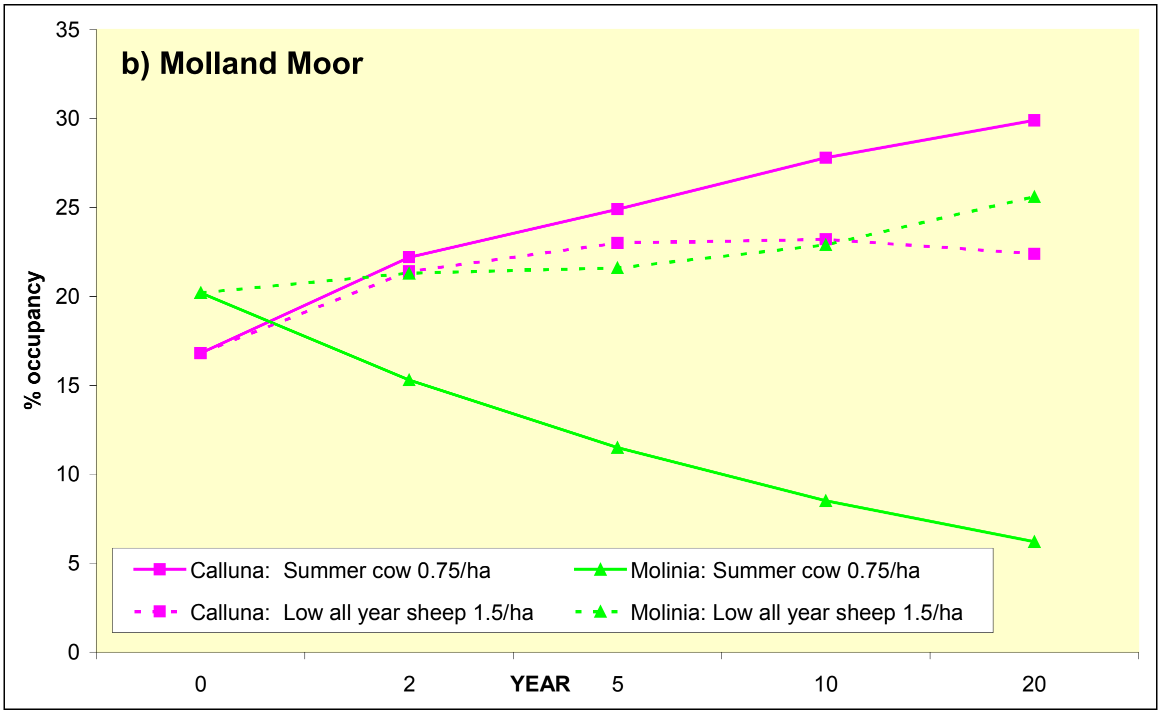


Table 4 **Percentage occupancy of key species at the Whole Moor scale under different grazing regimes at Redesdale, Molland Moor, Pwllpeiran and Birkbeck Common**

Grazing scenarios	REDESDALE		MOLLAND MOOR			PWLLPEIRAN		BIRKBECK COMMON		
	Calluna	*Molinia*	*Calluna*	*Molinia*	*Vaccinium*	*Nardus*	Broad-leaved grasses	*Nardus*	Broad-leaved grasses	*Calluna*
Starting occupancy	***20.0***	***29.0***	***16.8***	***20.2***	***23.3***	***22.3***	***13.9***	***35.5***	***7.8***	***13.0***
1a) Baseline	20.9	42.3	10.6	44.1	10.1	---	---	39.3	5.5	11.3
1b) All yr sheep 1.5 ha^{-1}	21.7	43.1	22.4	25.6	26.8	15.2	23.4	36.5	11.2	16.6
1c) All yr sheep 0.66 ha^{-1}	24.2	41.6	22.9	23.9	28.4	15.7	23.9	35.9	10.6	16.9
2. No Grazing	23.4	39.5	24.3	22.6	29.5	15.0	21.9	35.9	10.9	17.7
3a) Summer sheep 2.1 ha^{-1}	23.8	40.4	---	---	---	14.8	23.4	---	---	---
3b)Summer sheep 0.66 ha^{-1}	23.9	42.7	---	---	---	14.9	23.3	---	---	---
4a) Summer cattle 0.75 ha^{-1}	27.4	27.2	29.9	6.2	32.8	19.0	12.1	36.3	3.0	19.4
4b) Sum. cattle 0.225 ha^{-1}	25.0	37.8	25.7	16.5	30.1	16.8	18.4	38.1	5.6	18.5
5a) Mixed: 0.75 sum. cows + 0.66 all yr sheep ha^{-1}	25.6	28.9	29.8	6.6	34.3	19.5	10.8	38.0	3.1	18.9
5b)Mixed: 0.225 sum cows + 0.66 all yr sheep ha^{-1}	23.7	36.5	---	---	---	17.8	19.7	38.0[a]	6.3[a]	12.3[a]
5c) Mixed: 0.75 sum.. cows + 1.5 all yr sheep ha^{-1}	26.0	28.4	---	---	---	21.0	12.2	36.4[b]	2.9[b]	20.6[b]
6a) Short rotation: 2.1 sheep ha^{-1} for 2 yr in 5	23.2	42.5	---	---	---	14.7	23.2	---	---	---
6b) Short rotation: 0.75 cows ha^{-1} for 2 yr in 5	24.2	36.0	---	---	---	17.5	17.9	---	---	---
6c) Long rotation: 2.1 sheep ha^{-1} for 1 yr in 5	22.2	42.1	---	---	---	13.3	22.5	---	---	---
6d) Long rotation: 0.75 cows ha^{-1} for 1 yr in 5	25.4	36.5	---	---	---	15.1	19.8	35.9	7.7	17.9

(compare Figures 6a & 6b); a difference that may be due to heterogeneity in the distribution of *Molinia* across the different plant communities at the two sites.

Effect of different grazing regimes at the plant community scale

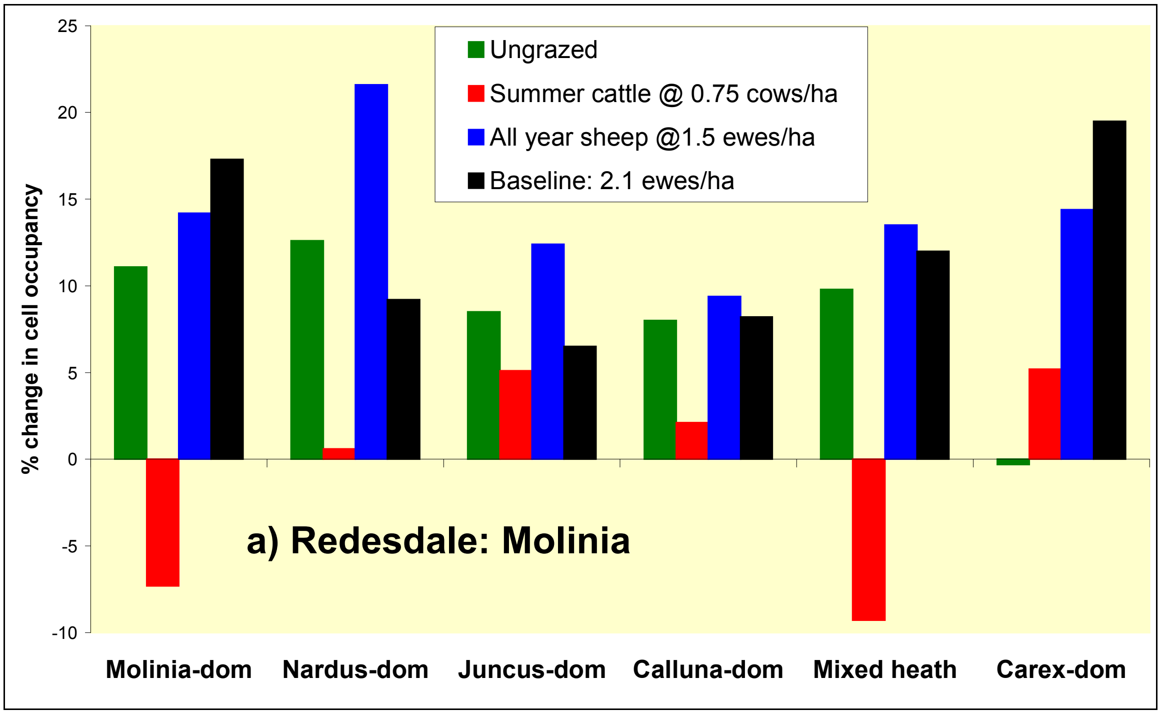
Comparison of predicted change in *Molinia* occupancy under summer cattle grazing at Redesdale, suggested that there was considerable variation between plant communities in the size and direction of change (Figure 7a). Under summer cattle scenarios (Regimes 4a, 5a and 5c Table 5), *Molinia* was predicted to decline in the *Molinia*-dominated and Mixed Heath communities where it was dominant and to increase in *Juncus*-, *Calluna*- and *Carex*-dominated communities, where it was infrequent (Figure 7a). The size of the predicted increase was, however, smaller in all cases than that predicted for all year low sheep grazing (Figure 7a).

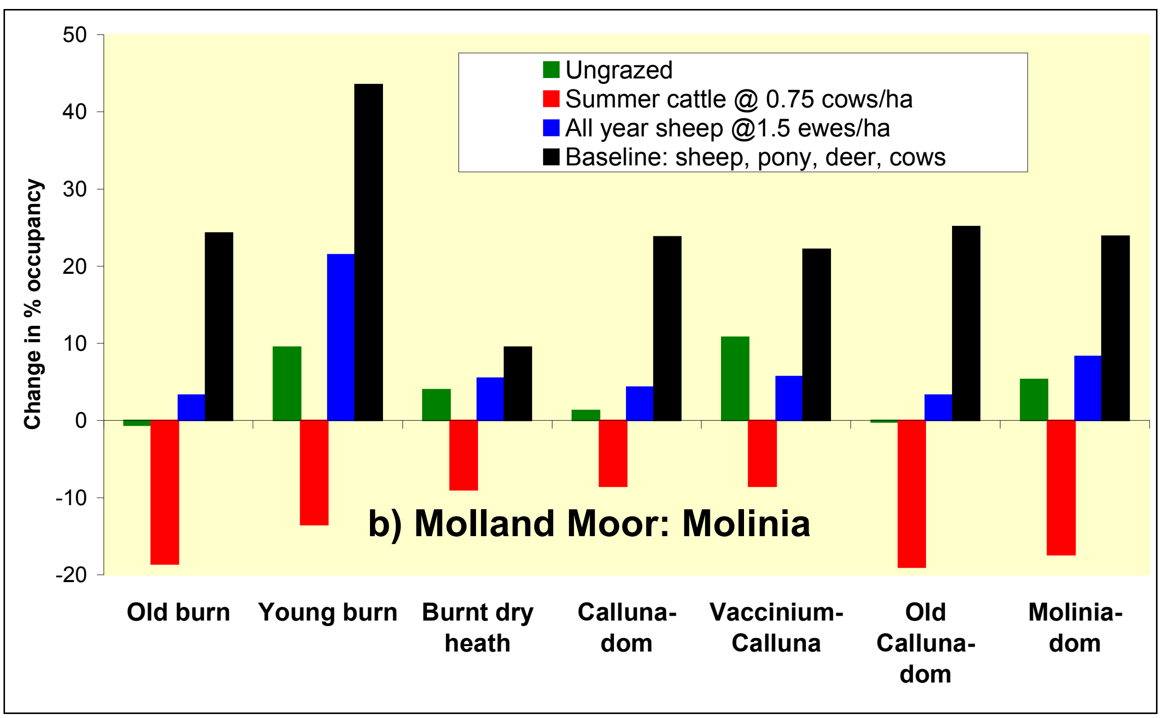
In the absence of grazing (Regime 2) *Molinia* occupancy was predicted to increase in five of the six plant communities at Redesdale (Figure 7a). This suggests that *Molinia* has the potential to dominate this site if it is left unmanaged. Similar or greater increases in *Molinia* occupancy were also predicted for all year low and high (baseline) sheep grazing (Figure 7a) suggesting that under these regimes the competitiveness of *Molinia* might be enhanced.

At Molland Moor, summer cattle grazing was predicted to result in a larger and more consistent reduction in *Molinia* across all communities than at Redesdale (*cf.* Figures 7a & 7b). This reduction was predicted as greatest in Old Burn, Old *Calluna*- and Molinia-dominated communities (Figure 7b)

Cattle will eat *Molinia,* particularly the current year's growth, and tend to forage by selecting large patches of digestible vegetation (a condition included in the model). At Molland, *Molinia* was dominant in four of the seven plant communities and frequent in the remaining three (mean occupancy of *Molinia* ranged from 9-28% across the seven communities Table 6). The frequent occupancy and even distribution of *Molinia* across the different communities at Molland might be expected to result in a more uniform distribution of cattle grazing.

Figure 7 **Percentage change in *Molinia* occupancy under Zero grazing, summer cattle (0.75 cows ha $^{-1}$), all year sheep (1.5 ewes ha $^{-1}$) and Baseline grazing scenarios**





This would limit the opportunities for *Molinia* to increase its occupancy, and could account for the greater reduction in *Molinia* occupancy predicted for Molland under summer cattle grazing.

At Redesdale, *Molinia* was dominant in only two communities and its mean occupancy ranged from 0-61% across the six communities (Table 5). Heterogeneity in the distribution of *Molinia* across the plant communities at Redesdale might be expected to result in a concentration of cattle grazing on communities where *Molinia* is dominant. Conversely, communities with infrequent *Molinia* might remain relatively ungrazed (especially if dominated by unpalatable/less preferred species present such as Rushes and *Nardus*), and in time could act as a refuge for *Molinia* persistence.

Under the baseline and all year sheep scenarios at Molland Moor (regime 1b, Table 6), *Molinia* occupancy was predicted to increase in all communities (Figure 7b) in a manner similar to that predicted for Redesdale (*cf.* Figure 7a). Sheep are more selective grazers than cattle - selecting individual plants within a community, and may be less influenced by the patch size and heterogeneity in species distribution between different plant communities. If so, then differences in the distribution of *Molinia* between plant communities on the two sites would have a limited effect on the effect of low sheep grazing on *Molinia* occupancy.

At both sites, Calluna enhancement was predicted to be greatest under summer cattle grazing. Calluna was predicted to increase in all communities under summer cattle but the size of the increase was predicted to be generally lower and much more variable across the plant communities at Redesdale than at Molland (Figures 8a & 8b). This variation may again reflect greater heterogeneity in the distribution of plant species and foraging effort by cattle at Redesdale compared to Molland.

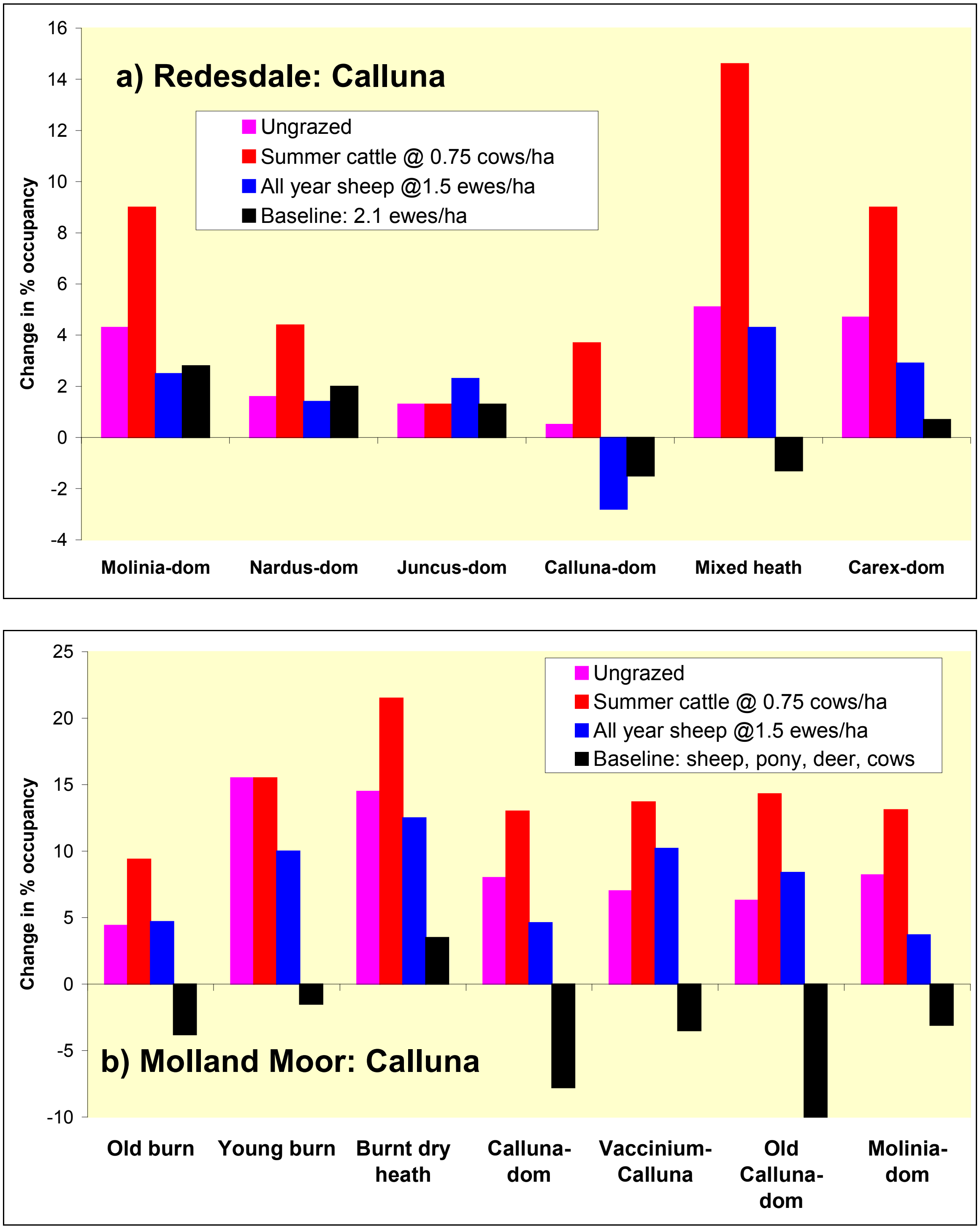
Table 5 Percentage occupancy of *Calluna* and *Molinia* in six plant communities at Redesdale, following 20 year simulations of different grazing scenarios

Grazing scenarios	*Molinia*-dominated		***Nardus*-dominated**		*Juncus*-dominated		*Calluna*-dominated		Mixed heath		*Carex*-dominated	
	Calluna	*Molinia*	*Calluna*	*Molinia*	*Calluna*	*Molinia*	*Calluna*	*Molinia*	*Calluna*	*Molinia*	*Calluna*	*Molinia*
Starting occupancy	***2.9***	***61.2***	***0***	***14.6***	***0***	***0.3***	***83.5***	***4.5***	***31.0***	***37.9***	***4.3***	***7.8***
1a) Baseline:	5.7	78.5	2.0	23.8	1.3	6.5	82.0	12.7	29.7	49.9	5.0	27.3
1b) 1.5 sheep ha^{-1}	5.4	75.4	1.4	36.2	2.3	12.7	80.7	13.9	35.3	51.4	7.2	22.2
1c) 0.66 sheep ha^{-1}	7.5	74.8	3.0	41.0	2.0	8.3	81.6	14.4	40.6	44.7	13.3	19.3
2. No Grazing	7.2	72.3	1.6	27.2	1.3	8.8	84.0	12.5	36.1	47.7	9.0	7.5
3a) High sum sheep	8.1	73.8	2.6	28.6	2.3	8.5	86.4	10.1	33.1	50.6	10.5	21.2
3b) Low sum sheep	7.7	77.7	5.0	31.2	2.0	7.5	84.7	10.6	33.6	51.0	12.0	27.5
4a) High sum cow	11.8	53.9	4.4	15.2	1.3	6.2	87.2	6.6	45.6	28.6	13.3	13.0
4b) Low sum. Cow	8.6	69.8	1.4	26.2	0.3	7.5	87.4	8.7	41.6	42.7	10.5	25.7
5a) Mixed: high cow + low sheep	10.4	55.4	1.6	20.2	1.2	2.3	86.5	9.0	42.7	31.7	9.5	15.2
5b) Mixed: low cow + low sheep	7.3	67.2	2.6	28.8	1.3	5.2	84.7	9.4	38.9	42.6	8.0	21.3
5c) Mixed: high cow + ESA sheep	12.9	55.1	3.2	16.8	2.2	3.8	85.1	7.1	43.6	32.6	9.2	15.3
6a) Short rotation: sheep for 2 yr in 5	8.4	75.4	1.2	35.2	1.2	3.8	82.9	14.0	37.9	51.0	6.5	27.5
6b) Short rotation: cattle for 2 yr in 5	7.9	67.7	4.2	29.6	2.2	6.5	85.0	10.0	35.6	38.4	12.0	18.0
6c) Long rotation: sheep for 1 yr in 5	7.0	75.1	1.2	29.8	1.5	7.5	80.1	14.5	34.4	50.7	9.8	25.8
6d) Long rotation: cows for 1 yr in 5	9.2	68.4	0.8	28.2	1.3	7.7	88.9	8.1	40.6	42.7	10.7	18.0

Table 6 **Percentage occupancy of *Calluna* and *Molinia* in seven plant communities at Molland Moor, following 20 year simulations of different grazing scenarios. *C.v. – Calluna vulgaris, M.c. Molinia caerulea***

Grazing scenarios	Old burn		Young burn		Burnt heath		*Calluna*-dominated		*Vaccinium-Calluna*		Old *Calluna*		*Molinia*-dominated	
	C.v.	*M.c.*	*C.v.*	*M.c.*	*C.v.*	*M.c.*	*C.v.*	*M.c.*	*C.v.*	*M.c.*	*C.v.*	*M.c.*	*C.v.*	*M.c.*
Starting occupancy	***8.0***	***25.0***	***8.0***	***21.0***	***4.0***	***9.0***	***25.0***	***11.3***	***14.0***	***14.0***	***24.0***	***26.0***	***5.0***	***28.0***
Baseline: sheep, cattle, ponies, deer	4.2	49.3	6.5	44.5	7.5	18.5	17.2	35.1	10.5	36.2	14.0	51.1	1.9	51.9
1b) All year sheep @ 1.5 ha^{-1}	12.7	28.3	18.0	42.5	16.5	14.5	29.6	15.6	24.2	19.7	32.4	29.3	8.7	36.3
1c) All year sheep @ 0.66 ha^{-1}	12.4	24.7	23.0	27.5	9.5	20.5	31.2	17.1	23.5	21.0	30.8	25.4	10.1	32.4
2. No Grazing	12.4	24.4	23.5	30.5	18.5	13.0	33.0	12.6	21.0	24.8	30.3	25.8	13.2	33.3
4a) High summer cattle @ 0.75 ha^{-1}	17.4	6.4	23.5	7.5	25.5	0	38.0	2.8	27.7	5.5	38.3	7.0	18.1	10.6
4b) Low summer cattle @ 0.225 ha^{-1}	13.9	22.8	28.5	19.0	17.5	2.0	35.1	9.6	20.7	16.0	32.9	18.7	12.8	22.8
5a) Mixed: high summer cattle + low all year sheep @ 0.75 + 0.66 ha^{-1}	17.9	10.1	23.5	17.0	19.5	3.5	37.5	2.7	30.2	4.2	39.4	7.8	17.3	9.6

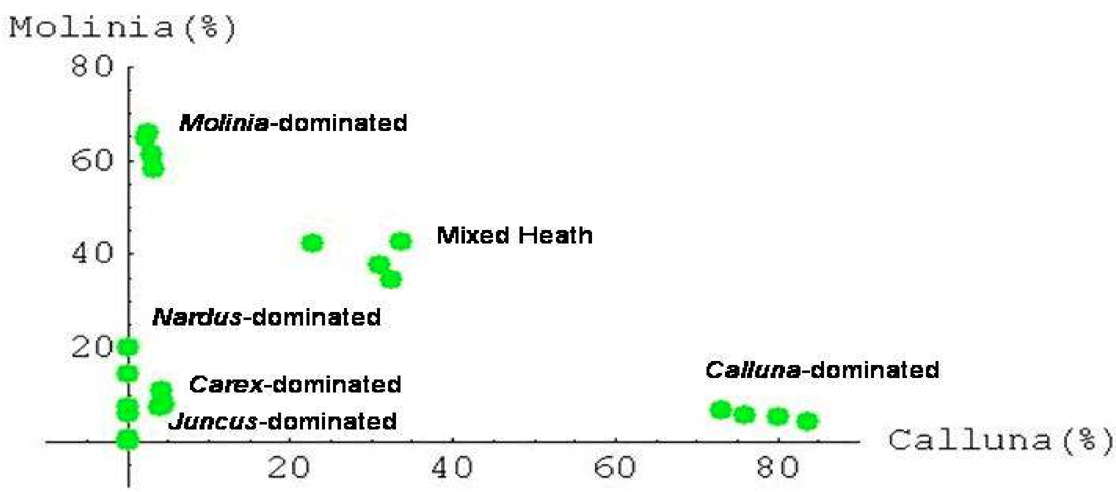
Figure 8 **Percentage change in *Calluna* occupancy under Zero grazing, summer cattle (0.75 cows ha $^{-1}$), all year sheep (1.5 ewes ha $^{-1}$) and Baseline scenarios at a) Redesdale (baseline @ 2.1 ewes ha^{-1}) and b) Molland Moor (baseline @ 0.63 sheep, 0.022 .ponies, 0.044 deer & 0.147 cattle ha^{-1})**



Grazing and the competitive relationship between Calluna and Molinia

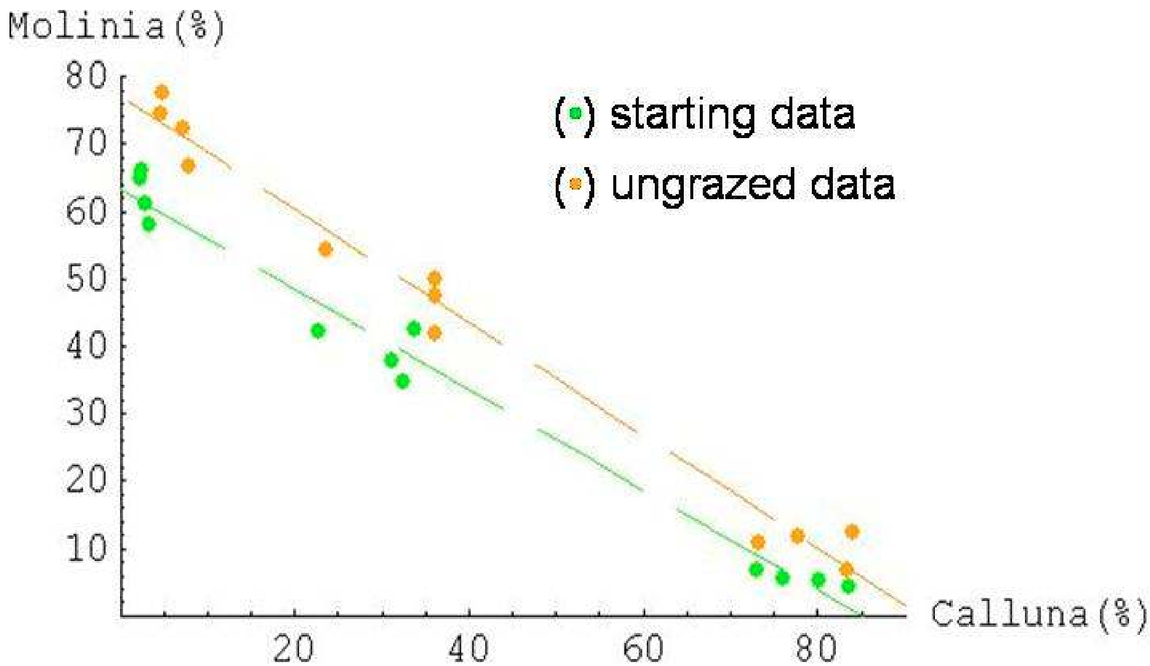
Data for the mean starting occupancy of *Calluna* and *Molinia* at Redesdale provided some evidence for direct competition between the two species in Mixed Heath, *Calluna*- and *Molinia*-dominated communities where one or both of the species were abundant (Figure 9). No relationship was evident in *Nardus-, Juncus*- and *Carex*-dominated communities, where top cover of both species was low (Figure 9). To determine whether grazing might potentially influence of competition between *Calluna* and *Molinia*, the predicted occupancy for the two species following 20 years of sheep, cattle or No grazing was plotted and compared with the starting relationship.

Figure 9 The starting occupancy of *Calluna* and *Molinia* in the six plant communities at Redesdale



Under No Grazing, the gradient of the competitive relationship was predicted to increase, suggesting that *Molinia* would replace *Calluna* at a faster rate under this regime (Figure 10). In addition, a large predicted increase in the intercept value suggested that *Molinia* might also be competing with and replacing other species such as *Nardus*, *Carex* and Mosses (Table 7). Thus, a regime of No Grazing might be expected to benefit *Molinia* by increasing its competitive vigour with both *Calluna* and other species present in the community.

Figure 10 Predicted *Calluna-Molinia* competition gradient in *Molinia*-dominated, Mixed Heath and *Calluna*-dominated communities at Redesdale, after 20 years of No Grazing. Gradient for the starting data for each community is also shown



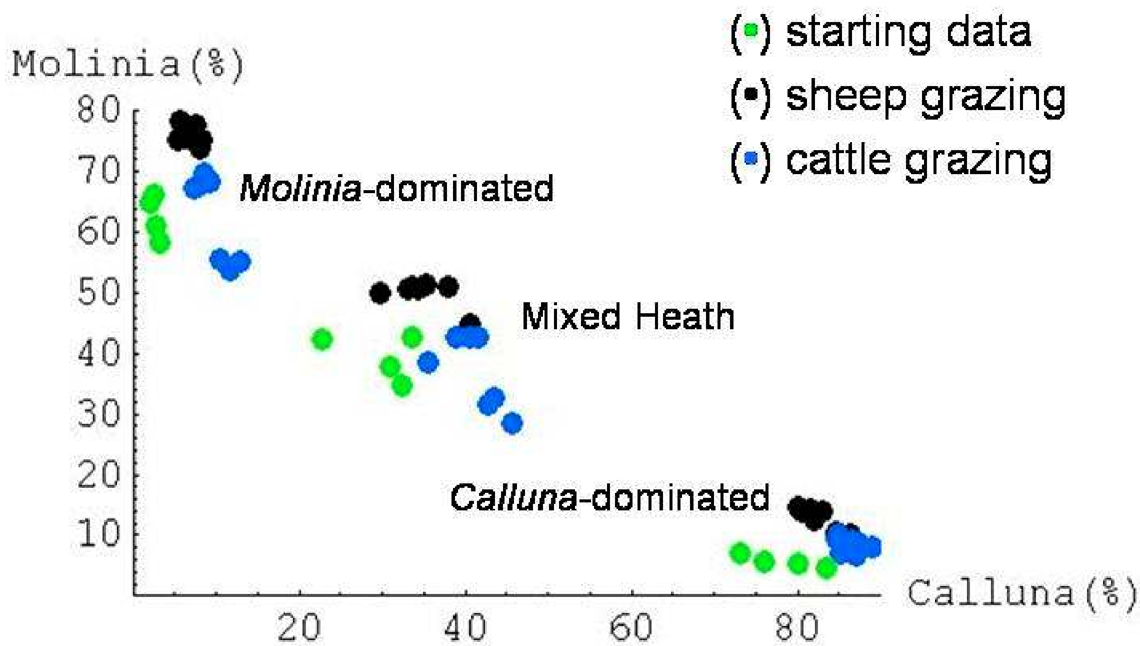
Comparison of predicted *Calluna* and *Molinia* occupancy under different sheep and cattle scenarios, suggested that *Molinia* occupancy, in communities where it is abundant, would show a greater increase under sheep grazing than under cattle (Figure 11). Under low sheep grazing, the *Calluna-Molinia* competition gradient was predicted to increase by 10.9% compared to the starting data but to show little difference from the competition gradient for No Grazing (Table 7). The competition gradient predicted for all cattle scenarios was lower than that for No Grazing and slightly lower than that for the starting data (Table 7). This reduction was, largely due to scenarios with High Summer Cattle where the gradient for the competition relationship is lower than those for the No Grazing and starting data (Table 7). This suggests that high cattle grazing may favour *Calluna* by suppressing any increase in *Molinia*. Under Low Summer Cattle or Rotational regimes, the *Calluna-Molinia* competition gradient was similar to the Starting data, but lower than that predicted for No Grazing (Table 7).

Table7 Predicted competition relationships for *Calluna* and *Molinia* under different grazing regimes

Grazing scenarios	Intercept	Gradient
Starting data	63.3	-0.744
Ungrazed	77.1	-0.838
Sheep regimes	80.5	-0.825
All cattle regimes	68.2	-0.705
High cattle regimes (0.75 cows/ha/year)	60.9	-0.629
Low or rotational cattle regimes	73.0	-0.748

Intercept values obtained for sheep and Low or Rotational cattle regimes were similar to that obtained for No Grazing (Table 7), suggesting that the increase in *Molinia* abundance is also driven by its replacement of other plant species. This was not predicted for High Cattle (Table 7). In *Nardus-, Juncus*- and *Carex*-dominated communities where little *Calluna-Molinia* competition was predicted, both species appeared to replace species such as *Carex, Deschampsia*, Fine-leaved grasses and *Nardus.* This replacement process would appear to be the principal mechanism driving the increase in both *Calluna* and *Molinia* in these communities.

Figure 11 Predicted end-points for % occupancy of *Calluna* & *Molinia* in *Molinia*-dominated, *Calluna*-dominated and Mixed Heath communities after 20 years of different sheep and cattle grazing scenarios



Nardus-Calluna and Nardus-Agrostis heath

Effect of different grazing scenarios at the whole moor scale

Model predictions for species change in *Nardus-Agrostis* heath at Pwllpeiran indicated that rotational (6a, 6c), summer (3a, 3b) and low (1c) sheep grazing scenarios would be the most effective in meeting the management objectives for this site (Table 4). Under these scenarios a slow but steady decrease in *Nardus* was predicted (Figure 12a). *Nardus* was also predicted to decline under mixed or summer cattle grazing scenarios (4a, 4b and 5a) but by a smaller percentage

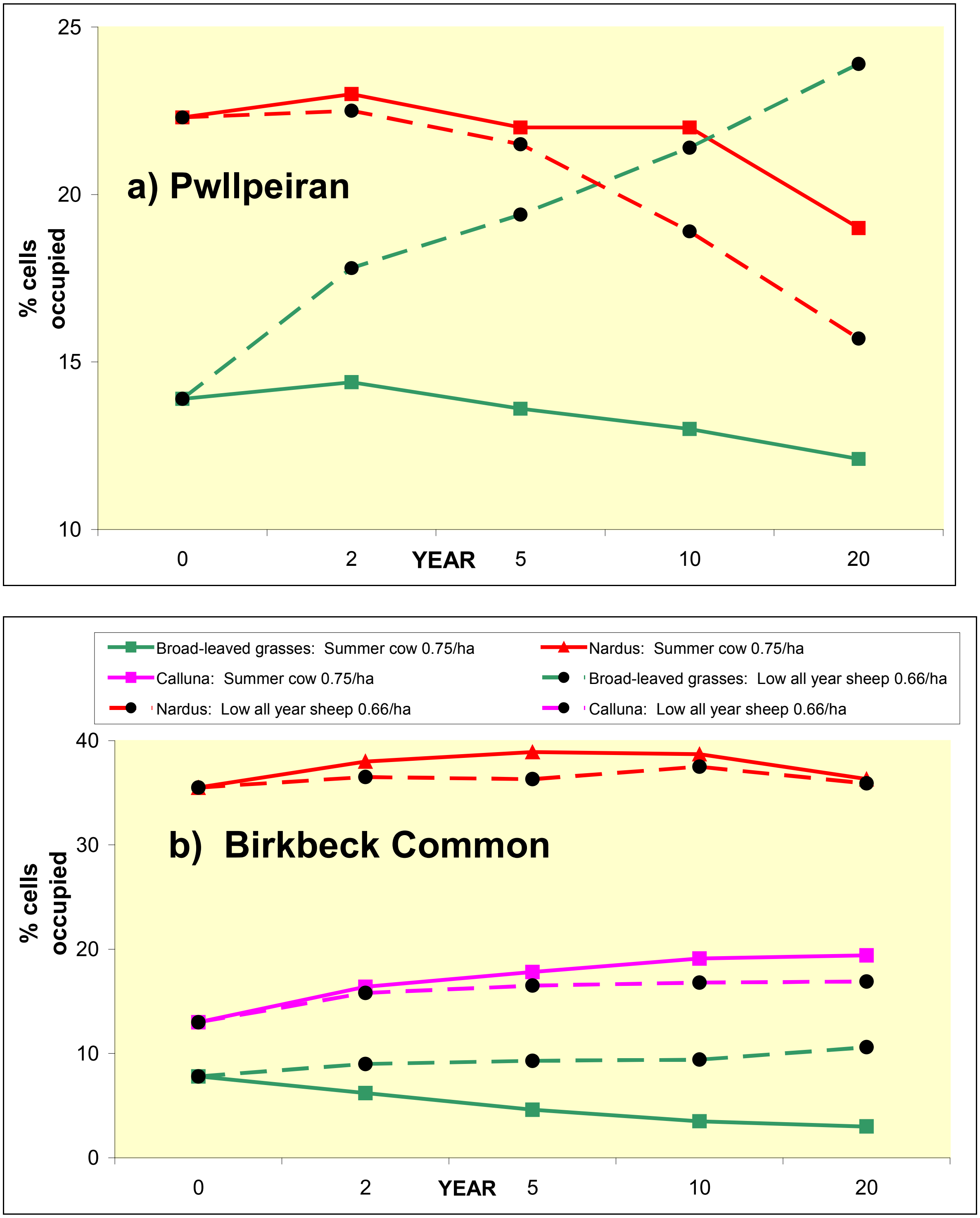
(Figure 12a). Broad-leaved grasses, on the other hand, were predicted to increase steadily under low sheep grazing but to decline under high summer cattle (4a, 5a and 5c) (Figure 12a). The occupancy by rushes was predicted to increase by 7-10% under scenarios with summer cattle and by 3-7% under sheep.

At Birkbeck Common, species change was greatest under the baseline scenario of all year sheep, ponies and seasonal cattle. Under this scenario, the whole moor means of *Calluna* and Broad-leaved grasses were predicted to decline, and those of *Nardus* and Rushes predicted to increase (Table 4*).*

At Birkbeck, little difference was predicted between the effects of sheep only, summer cattle and mixed grazing scenarios on *Nardus* and *Calluna* (Figure 12b). The mean whole moor occupancy of *Nardus* was maintained under all regimes and the mean whole moor occupancy of *Calluna* was predicted to increase by 4-7% (Table 4). There were differences in the effects of summer cattle and sheep on Broad-leaved grasses, which were predicted to decline under summer cattle and to increase under low sheep grazing (Figure 12b).

A clear difference in the rate of species change was apparent between the two sites: with change predicted to occur more rapidly at Pwllpeiran than at Birkbeck, particularly under low sheep grazing (*cf.* Figs. 12a & 12b). This difference may be attributed to differences in the distribution of *Nardus* between the different plant communities at the two sites.

Figure 12 Change in *Nardus,* Broad-leaved grasses and *Calluna* occupancy under summer cattle (0.75 cows ha $^{-1}$) and all year sheep (0.66 sheep ha $^{-1}$) grazing at a) Pwllpeiran and b) Birkbeck Common



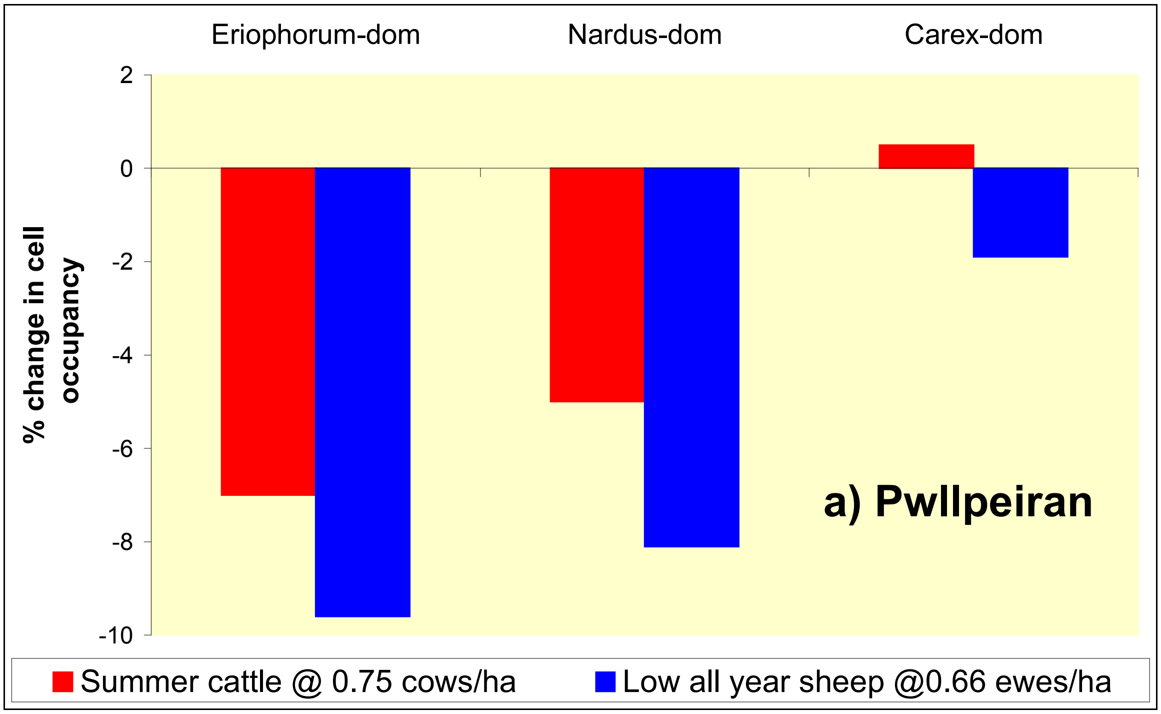
Effect of different grazing regimes at the plant community scale

Species change within the three communities at Pwllpeiran was similar to that predicted for the whole moor (Table 8). Thus *Nardus* was predicted to show a greater reduction in occupancy (Figure 13a) and Broad-leaved grasses a greater increase in occupancy under rotational, all year low or summer sheep grazing than under summer cattle, mixed or rotational cattle grazing (Table 8). Overall, the outcomes for low sheep grazing were predicted to show little difference from the No Grazing scenario (Table 8), suggesting that low sheep grazing may have little overall impact on species change on *Agrostis-Nardus* heath.

Species change at Birkbeck Common varied considerably between the seven communities and from the species' means predicted for the Whole Moor (Figure 13b for *Nardus*). As at Pwllpeiran, a clear difference was predicted between the effects of different livestock species on Broad-leaved grasses. These grasses were predicted to decline under summer cattle in 5 of the 7 communities and to increase under low sheep grazing in 4 of the 7 plant communities (Table 9). However, with the exception of Bent-Fescue Grassland, little difference was predicted between the effects of low sheep and summer cattle on *Nardus* (Figure 13b). In both cases, *Nardus* was predicted to decline in Rough Acid Grassland where it was dominant and to increase in five of the remaining six plant communities.

In Bent-Fescue grassland, a clear difference was predicted between the effect of low sheep and summer cattle grazing on *Nardus*. Under low sheep grazing, *Nardus* was predicted to decline in Bent-Fescue grassland but to increase under summer cattle grazing (Figure 14a). Conversely Broad-leaved grasses (which were dominant in Bent-fescue grassland), were predicted to increase under all year sheep and no grazing scenarios (1b, 1c & 2) but to decrease by up to 50% under all scenarios involving summer cattle grazing (Table 9 and Figure 14a). This loss of broad-leaved grasses was accompanied by an increased occupancy of dwarf shrub species (*Calluna* and *Erica tetralix*) and Rushes which were all

Figure 13 **Predicted change in *Nardus* occupancy for different plant communities at a) Pwllpeiran and b) Birkbeck Common grazed by summer cattle @0.75 cows ha^{-1} or all year low sheep @ 0.66 sheep ha^{-1}**



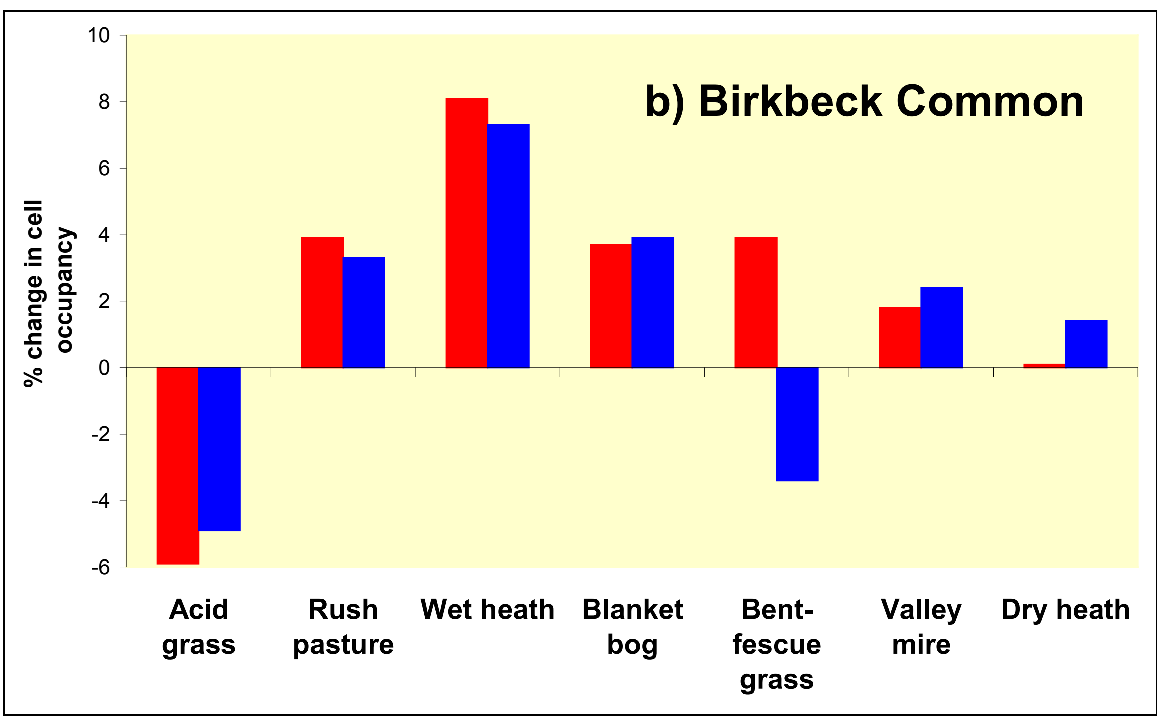


Table 8 Percentage occupancy of *Nardus* and Broad-leaved grasses under different grazing regimes at Pwllpeiran

Grazing scenarios	*Eriophorum*-dominated		*Nardus*-dominated		*Carex*-dominated	
	Nardus	Broad-leaved grasses	*Nardus*	Broad-leaved grasses	*Nardus*	Broad-leaved grasses
Starting occupancy	17	8	25.7	15.3	17.5	13.7
1b) All year sheep 1.5 ha^{-1}	9	11.7	16.9	23.4	14.3	29.4
1c) All year sheep 0.66 ha^{-1}	7.4	11.4	17.6	24.8	15.6	22.9
2. No Grazing	7.1	7.0	16.9	24.2	14.8	24.0
3a) Summer sheep 2.1 ha^{-1}	6.7	7.0	16.1	23.6	15.3	25.7
3b) Summer sheep 0.66 ha^{-1}	8.6	12.2	17.3	25.8	13.2	26.2
4a) Summer cattle 0.75 ha^{-1}	10.0	5.4	21.0	12.8	19.0	13.9
4b) Sum. cattle 0.225 ha^{-1}	7.2	8.2	18.8	20.3	18.9	13.9
5a) Mixed: 0.75 sum. cows + 0.66 all yr sheep ha^{-1}	8.0	2.4	21.1	11.7	21.9	12.9
5b) Mixed: 0.225 sum. cows + 0.66 all yr sheep ha^{-1}	10.6	8.2	19.9	20.6	16.6	23.3
5c) Mixed: 0.75 sum. cows + 1.5 all yr sheep ha^{-1}	14.6	7.0	23.1	13.5	19.6	12.7
6a) Rotation: 2.1 sheep ha^{-1} for 2 yr in 5	9.2	9.1	16.6	24.7	13.1	27.0
6b) Rotation: 0.75 cows ha^{-1} for 2 yr in 5	8.6	6.5	19.2	19.0	18.2	21.1
6c) Rotation: 2.1 sheep ha^{-1} for 1 yr in 5	3.7	9.9	14.9	23.4	14.6	26.9
6d) Rotation: 0.75 cows ha^{-1} for 1 yr in 5	7.7	6.9	17.2	20.5	14.1	24.6

Table 9 Percentage occupancy of key species in seven plant communities at Birkbeck Common, following 20 year simulations of different grazing scenarios. *Nardus* (*N.s.*), Broad-leaved grasses (BLG) and *Calluna* (*C.v.*), Rushes (Rs), *Eriophorum* (*E.v.*), *Erica tetralix* (*E.t.*)

Grazing scenarios	Rough acid grass	Rush and rank pasture		Wet heath			Blanket bog		Bent-fescue grassland			Valley mire		Dry heather heath	
	N.s.	BLG	Rs	*C.v.*	*E.v.*	*E.t.*	*E.v.*	*E.t.*	*C.v.*	*N.s.*	BLG	BLG	Rs	*C.v.*	BLG
Starting occupancy	***87.0***	***12***	***69***	***52.0***	***14.0***	***13.0***	***48.0***	***7.0***	***0***	***18***	***53***	***6.0***	***71.0***	***78***	***6***
Baseline: sheep, cattle, ponies	83.6	2.6	89.0	35.7	11.7	11.7	43.1	9.5	4.8	25.2	33.7	0.5	90.0	63.6	3.8
1b) All year sheep @ 1.5 ha^{-1}	82.0	9.0	82.0	56.2	7.9	8.8	53.0	8.6	7.6	15.9	62.4	4.8	85.7	83.0	4.6
1c) All year sheep @ 0.66 ha^{-1}	82.4	6.6	81.1	56.8	7.7	11.3	46.5	9.7	8.1	14.6	59.8	3.7	87.0	82.1	4.9
2. No Grazing	8105	7.6	81.3	58.1	8.8	10.9	44.2	10.7	8.8	14.3	63.9	2.9	85.5	86.6	4
4a) High summer cattle @ 0.75 ha^{-1}	81.1	0.7	90.1	59.7	4.5	16.6	29.3	21.3	18.1	21.9	22.1	0.1	90.5		
4b) Low summer cattle @ 0.225 ha^{-1}	83.8	4.9	84.3	60.2	6.7	13.9	47.3	11.6	12.2	24.7	36.4	0.9	90.5	87.0	1.0
5a) Mixed: high summer cattle + low all year sheep @ 0.75 + 0.66 ha^{-1}	83.8	2.1	87.9	62.1	4.0	13.3	30.2	19.8	13.6	27.9	21.8	1.5	91.5	88.1	1.9
5b) Mixed: low sheep +ponies @ 0.66 + 0.06 ha^{-1}	82.8	0.9	90.1	40.2	12.0	11.5	45.4	10.4	4.1	22.0	37.9	1.9	87.9	67.3	7.1
5c) Mixed: high summer cattle + ponies @ 0.75 + 0.06 ha^{-1}	80.8	0.0	91.4	64.4	4.6	11.0	27.8	17.3	15.9	24.4	21.2	0.4	89.5	91.4	0.3
6d) Long rotation: 0.75 cows ha^{-1} for 1 yr in 5	81.2	6.3	83.4	58.9	5.2	13.6	49.1	10.8	10.9	19.8	46.0	0.8	89.4	86.8	1.9

predicted to show greater increases in the Bent-Fescue community under summer cattle than under low sheep grazing (Table 9).

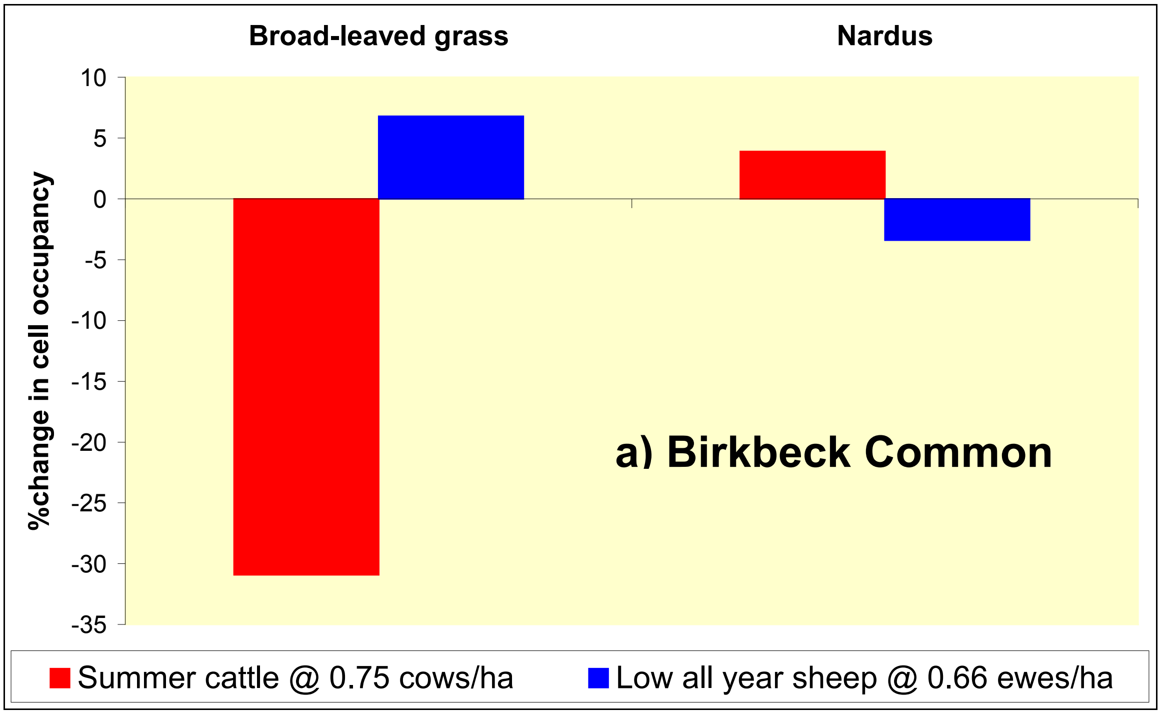
A similar effect on *Nardus* and Broad-leaved grasses was predicted for the *Nardus*-dominated community at Pwllpeiran. As noted earlier Broad-leaved grasses were predicted to decline under summer cattle and to increase under low sheep grazing (Figure 14b). Conversely *Nardus* was predicted to show a smaller decrease under cattle than under low sheep grazing (Figure 14b). Unlike Birkbeck, the loss of Broad-leaved grasses from the *Nardus*-dominated community at Pwllpeiran was not accompanied by an increase in dwarf shrubs, as the starting occupancy of *Calluna* at this site was very low.

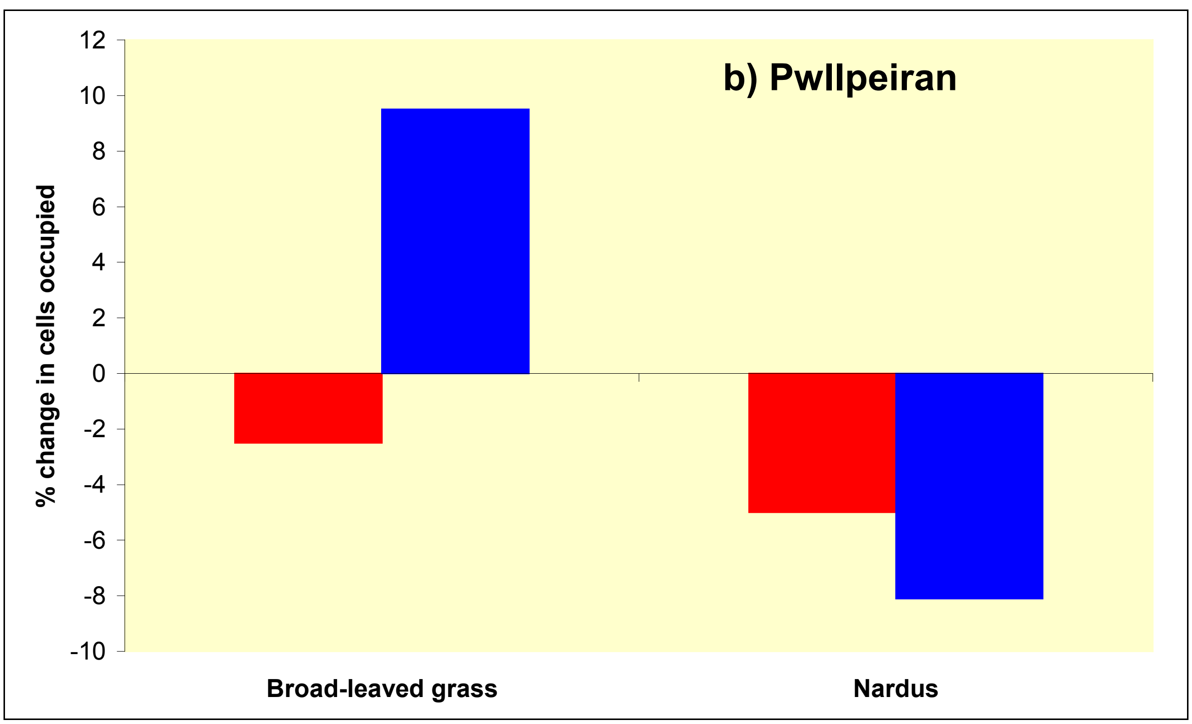
These predictions suggest an interaction between *Nardus* and Broad-leaved grasses in these grass-dominated communities. There is evidence from the literature that *Agrostis* sp. (the principal Broad-leaved grass species present), can out-compete *Nardus* when no grazers are present (Grime *et al.* 1988). Results from the model suggest that under No or low sheep grazing, Broad-leaved grasses increase in occupancy and can replace *Nardus.* Thus these regimes may affect *Nardus* indirectly by encouraging species competition.

Cattle on the other hand, are predicted to remove a significant proportion of the Broad-leaved grasses present in these grass-dominated communities. This may reduce the competitive pressure on *Nardus* and enable it to persist within the sward. However, by opening up the sward, cattle may enable dwarf shrubs and other plant species to establish and increase as predicted for Birkbeck.

The effect of grazing on *Nardus* and Broad-leaved grasses was predicted to show much greater consistency in the size and direction of change across the communities at Pwllpeiran than across those at Birkbeck Common (*cf.* Figures 13a and 13b). Both species groups were more evenly distributed across the three plant communities at Pwllpeiran (Table 8) than at Birkbeck. *Nardus* occupancy at Birkbeck Common ranged from 0-87% and Broad-leaved grasses from 0-53% across the seven plant communities. The greater heterogeneity in

Figure 14 **Predicted change in Broad-leaved grasses and *Nardus* occupancy under summer cattle @0.75 cows ha^{-1} or all year low sheep @ 0.66 sheep ha^{-1}in a) Bent-fescue grassland at Birkbeck Common and b) *Nardus-Agrostis* grassland at Pwllpeiran**



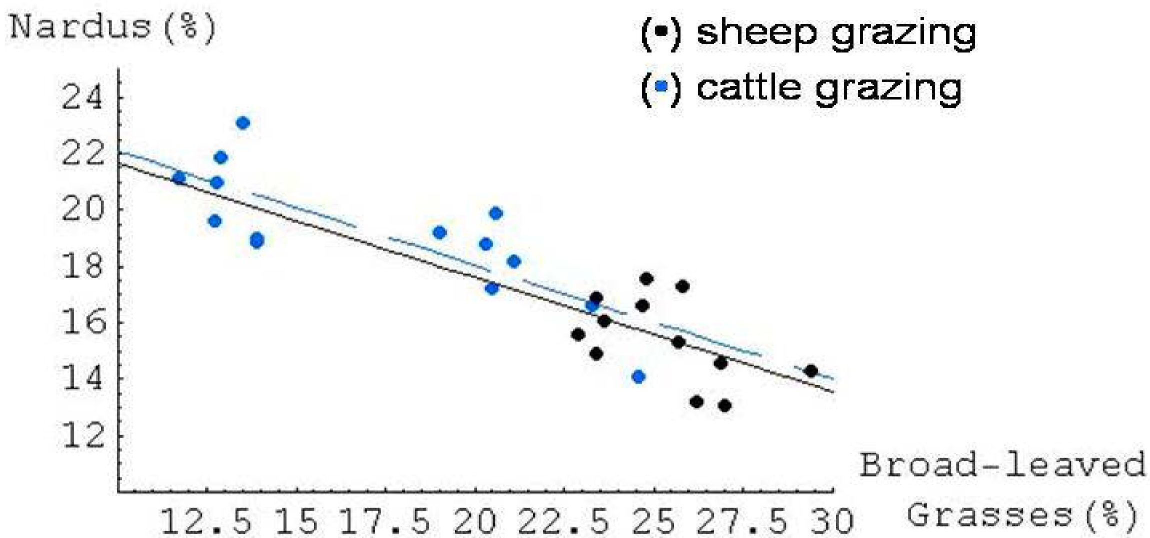


species distribution at Birkbeck may result in a more uneven utilisation of the different plant communities by livestock and hence greater variation in the size and direction of species change between communities. Consequently the overall rate of species change at Birkbeck is predicted to be slower than at Pwllpeiran.

Grazing and the relationships between *Nardus* and Broad-leaved Grasses

Model outputs, using data from Year 20 of each scenario, suggested that competition might occur between *Nardus* and broad-leaved grasses in *Nardus*- and *Carex* -dominated communities. Predicted competitive relationships did not differ between sheep and cattle grazing regimes, but cattle tended to be associated with a high occupancy of *Nardus* and sheep with a high occupancy of broad-leaved grasses (Figure 15). Since both species tend to prefer broad-leaved grasses in July and August, (though cattle are less selective and forage on larger grass patches), the lower occupancy of broad-leaved grasses under cattle might be due to their larger energy requirement and hence greater offtake. By reducing the occupancy of competitive broad-leaved grasses, cattle might enable *Nardus* to persist longer in the sward - particularly in the absence of competitive dwarf shrub species such as *Calluna* (*cf.* Birkbeck Common). Under low sheep grazing (*e.g.* 0.66 sheep ha^{-1}), broad-leaved grasses were predicted to increase and *Nardus* to decline. Given the low preference of sheep for *Nardus,* this decline is more likely to be due to competition between *Nardus* and other grasses rather than to direct grazing of *Nardus* by sheep.

Figure 15 Effect of sheep and cattle scenarios on the competitive relationship predicted for *Nardus* and Broad-leaved grasses in *Nardus-* and Carex-dominated communities at Pwllpeiran



DISCUSSION

Results from this modelling study highlight the role of three processes in driving vegetation change on upland heath and blanket bog. These are spatial heterogeneity in the distribution of key species (such as *Molinia*) across communities which influences their utilisation by livestock and the rate of species change across a site; grazing, which affects the condition of a species and the outcome of competition between species; and species competition, which influences the direction of species change.

Evidence for each of these processes occurring was present at each of the four sites used in the simulation studies. Overall model predictions compared well with field treatment data, although some differences were apparent in the cattle grazing treatments at Redesdale. These were due to local movements by cattle through *Calluna*-dominated vegetation, and highlight the potential for local site or one-off events to disrupt key drivers of vegetation change. Such results emphasise the importance of local vegetation monitoring for identifying and documenting the impact of such events on vegetation change.

The model is currently 2-dimensional and thus the representation of vegetation composition and measurement of the amount of each species present is necessarily simpler than that present in the field. Even so comparison of field data from the systems studies with predictions of species occupancy from the model, suggested that model outputs were robust in predicting the rate, direction and magnitude of vegetation change at both Whole Moor and plant community scales. The model outputs can only be used to provide indications of the amount (either of biomass or extent) of each species likely to occur under different grazing regimes because of its 2-dimensional design. All observations below relate to the outputs of the model runs,

The effectiveness of different livestock species in delivering vegetation management objectives varied with vegetation type. Thus in *Calluna-Molinia* heath, the foraging behavior of summer cattle was predicted to result in a direct effect on *Molinia* reducing its competitiveness and enabling dwarf shrubs and/or other species (*e.g.* Rushes, Broad-leaved grasses, *Deschampsia flexuosa*) to increase in extent. The selection of large patches of vegetation by cattle can lead to smaller patches of *Molinia* being overlooked, with the possibility that these patches might act as a refuge for the species. For example, *Molinia* was predicted to increase markedly in *Carex*-communities at Redesdale where its starting occupancy was low.

The effect of cattle on *Nardus* was more variable in *Nardus*-dominated heath (*Agrostis*-*Nardus* or *Calluna*-*Nardus*). Where *Nardus* was dominant in the sward (*e.g.* in rough acid grassland at Birkbeck), cattle were effective in reducing its extent. Where both *Nardus* and Broad-leaved grasses were frequent in the sward, cattle had a greater impact on the latter than on *Nardus* and a more variable outcome for vegetation change was predicted. If dwarf shrubs and/or Rushes were also present (as at Birkbeck), these were predicted to increase in extent and to replace the Broad-leaved grasses. If they were not present, then *Nardus* was predicted to persist in the sward (as at Pwllpeiran).

With respect to low sheep grazing, scenarios involving low all year, summer only or rotational sheep had little effect on the competitiveness of *Molinia* in *Calluna*-*Molinia* wet heath. Vegetation change under Low Sheep (0.66 ewes ha^{-1}) grazing was similar to that predicted for the No Grazing scenario. On *Nardus*-dominated heath, sheep offtake was insufficient to reduce the competitiveness of Broad-leaved grasses which increased in occupancy under all low sheep grazing scenarios at both Birkbeck and Pwllpeiran. At the same time a greater reduction in *Nardus* occupancy was predicted suggesting greater competition between *Nardus* and Broad-leaved grasses under low sheep grazing than under summer cattle.

Results from simulations at Redesdale, Pwllpeiran and Birkbeck suggested that whole site recovery of dwarf shrub vegetation at these three sites will be slow. At Redesdale and Birkbeck, heterogeneity in the distribution of *Molinia* and *Nardus* respectively resulted in a slower rate of dwarf shrub recovery than at Molland Moor where the distribution of *Molinia* across the different plant communities was more uniform and resulted in a faster increase in *Calluna* occupancy under summer cattle. At Pwllpeiran, recovery of *Calluna* was poor due its very low starting occupancy (<1%); and is likely to be hampered further by the lack of *Calluna* seed in the seedbank (see Appendix 4b).

The prediction that *Molinia* can increase by replacing 'Other Species' and that this process may be independent of grazing animals, represents a dilemma for the management of sites such as Redesdale, particularly as the 'Other Species' replaced varies between communities. Each community thus represents a potential source of *Molinia* increase even if *Molinia* abundance is successfully controlled in communities where it is dominant. An approach for managing these non-*Molinia* dominated communities might be to 'artificially' increase the abundance of dwarf shrub species within them by seeding. Establishment of dwarf shrubs within such communities might benefit from the initial absence of significant *Molinia* cover and from the presence of 'Other' species with which they can coexist and later replace. Under light summer grazing, dwarf shrubs might be expected to limit the expansion of *Molinia* within the community by indirect competition to replace 'Other' species. In this way, significant increases in *Molinia* in communities where it is not currently dominant might be averted. Clearly this is just an hypothesis that requires further study, but the management of *Molinia* in plant communities where it is a minor but vigorous component is important in order to limit the expansion of this highly competitive and successful species.

It is evident that the determination of Environmentally Sustainable grazing regimes will be influenced by the environmental and economic objectives for each site. Results from this study confirm that there is no universal set of prescriptions that is appropriate for maintaining or reversing the loss of the vegetation mosaic on upland moor. At the present time, livestock numbers are declining in the uplands which may present an additional challenge to managers trying to maintain the balance of dwarf shrubs to competitive grasses such as

Molinia. Simulation tools such as the model described here can help to identify those sites where change is both likely and achievable, but ultimately the actual choice of grazing regime will be driven by economics and the availability of appropriate hill stock as much as by environmental benefit.

ACKNOWLEDGEMENTS

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