REVISED

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD

Research and Development

Final Project Report

(Not to be used for LINK projects)

Date project completed:
31/03/1999

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Section 1 : Identification sheet

1. (a) MAFF Project Code: ~~BD0507~~ BD1209

(b) Project Title: Integrated Bracken Control and Vegetation Restoration: Ongoing Assessment with Follow-up Treatments

(c) MAFF Project Officer: Mr. Richard Brand-Hardy

(d) Name and address of contractor: University of Liverpool School of biological Sciences, Applied Ecology Research Group, Derby Building, Liverpool.
Postcode L69 3BX

(e) Contractor's Project Officer: Professor R.H. Marrs

(f) Project start date: 01/04/1996 Project end date: 31/03/1999

(g) Final year costs: **approved** expenditure: £59,557

actual expenditure: £59,557

(h) Total project costs / total staff input: **approved** project expenditure: £151,043

actual project expenditure: £151,043

***approved** staff input: 4.9 years

***actual** staff input: 4.9 years

(i) Date report sent to MAFF: 30/9/99

(j) Is there any Intellectual Property arising from this project? NO

***staff years of direct science effort**

Section 2 : Scientific objectives / Milestones

2. Please list the scientific objectives as set out in CSG 7 (ROAME B). If necessary these can be expressed in an abbreviated form. Indicate where amendments have been agreed with the MAFF Project Officer, giving the date of amendment.

1. To continue to monitor the impact of experimental treatments on bracken, its control, and replacement by other classes of vegetation.
2. To continue to monitor rehabilitation experiments on previously sprayed areas.
3. To continue to monitor bracken-front control experiments.
4. To increase the scope of the experiments by introducing follow-up treatments.
5. To investigate the impact of treatments on the bracken rhizome system.
6. To employ the results to develop and test models for post-control vegetation development.
7. To test existing models, BRACON and REBRA, for bracken growth and vegetation development.
8. To assess the techniques used in relation to practical bracken-infested land management.
9. To produce a series of annual reports and a final report.

3. List the primary milestones for the final year.

It is the responsibility of the contractor to check fully that ALL primary milestones have been met and to provide a detailed explanation if this has not proved possible

Milestones		Target date	Milestones met?	
Number	Title		in full	on time
1-3	Monitoring, treatment & data analysis of all experimental work	30/11/1998	YES	YES
5	Rhizome sampling and assessment	31/12/1998	NO	NO
6	Vegetation modelling and testing	28/02/1999	YES	YES
7	BRACON and REBRA testing	28/02/1999	YES	YES
8	Techniques assessed as practical management tools	28/02/1999	YES	YES

If any milestones have not been met in the final year, an explanation should be included in Section 5.

Section 3 : Declaration

4. I declare that the information I have given in this report is correct to the best of my knowledge and belief. I understand that the information contained in this form may be held on a computer system.

Signature: [signature] Date: 30/9/99

Name: Professor R.H. Marrs

Position in Organistation: Professor

Section 4 : Executive summary

INTRODUCTION

1. Bracken is a major weed causing problems for agriculture, conservation, forestry and recreation. It is difficult to eradicate.
2. The control of bracken is a multifactorial problem. Management requirements for land-use, and the land itself set constraints on the technologies available.

BACKGROUND

3. This research, commissioned by the Ministry of Agriculture, Fisheries and Food, is phase two of an ongoing project to assess methods to control bracken while at the same time ensuring that the underlying, or resulting vegetation matches the intended land use.

BRACKEN CONTROL AND VEGETATION RESTORATION

4. A series of seven experiments, to investigate combinations of bracken control and vegetation restoration treatments, have been running for up to six years. They have begun to produce practical information.
5. Spraying with asulam is an effective short-term measure for controlling bracken. Longer-term success can be achieved with cutting but this requires annual ongoing treatment. A combination of a single cut followed by spraying gives the best result. Cutting is very effective in the longer term. However it may be necessary to cut more than once per year, depending on the productivity of the bracken stand.
6. Any control treatment requires follow-up. Spot-spraying is recommended and should be applied at intervals, probably of about four to six years, depending on the response of the bracken stand.
7. Bracken's productivity may vary considerably between sites, even when only short distances apart. Thus two sites on the same estate may require differing intensities of treatment and careful monitoring.
8. *Calluna* heath can be established using seeding techniques. However this process is very slow and unpredictable due to extraneous factors such as the weather and invasion by weeds, especially if herbicide spraying has been used.
9. Restoration of upland grass ecosystems usually benefits from the fact that certain species of this system usually persist under the bracken canopy. After spraying, however, the weakened vegetation is susceptible to invasion by a range of weeds and less useful species.
10. Soil erosion is a real danger after the bracken canopy has been removed. Steep slopes and grazing exacerbate this problem.
11. Good quality grassland establishment may be helped by litter disturbance, though this is not really necessary at higher altitudes or on exposed sites, and low inputs of slow release fertilizer.

REMEDIAL TREATMENT OF SPRAYED SITES

12. Two experiments were set up in 1993 to investigate methods for re-establishing heath vegetation on sites with unsatisfactory vegetation development following spraying for bracken control.
13. Litter disturbance and application of heather seed may be necessary. However a nurse crop might hinder good establishment.
14. Choice of other management procedures depends on grazing potential. High grazing prevents establishment, but trampling helps to break down the bracken litter. Control of these factors for optimal heather establishment is site dependent and thus requires close monitoring.

CONTROL OF BRACKEN SPREAD

15. Two further experiments, set up in 1993, investigated the potential for controlling bracken encroachment.
16. Bracken was observed to encroach onto heath at a rate of about 0.4 - 0.5 m per year. Cutting was seen to reduce the encroachment rate by more than 60%. Spraying, on the other hand, acts to buy time but may not slow the rate of spread.

EXPERIMENTAL ASSESSMENT OF FOLLOW-UP TREATMENTS

17. A series of follow-up treatments were examined in conjunction with bracken control experiments. These included re-application of both asulam and fertilizer.
18. Spot spraying proved to be very successful, giving the same overall effect as initial spraying (better then 90% frond kill rate. Weed wiping was also successful but not as good as spot spraying; the currently available equipment was found to have practical problems in dense bracken.

TREATMENT EFFECTS ON BRACKEN RHIZOMES

19. Waterlogging of the sites due to bad weather restricted the sampling to four experiments only.
20. In general bracken control treatments have a significant effect on bracken rhizomes. The rhizome biomass is reduced by around 50% in five years.
21. The rhizome biomass was fairly constant at a regional level. The amount of rhizome varies significantly between regions. Since it is rhizome biomass that ultimately determines the effort required for control, there will be a regionally distributed cost effectiveness.

MOORLAND VEGETATION SUCCESSION AFTER BRACKEN CONTROL WITH ASULAM

22. Sites on the North York Moors have been monitored since 1990. Vegetation development scenarios have been developed.
23. Re-establishment of heather dominated moorland without intervention is a rare event. Successional trajectories back to bracken are moderated hy grazing pressure.

POST-CONTROL VEGETATION DEVELOPMENT MODELS

24. Previous modelling work has been compared with field data obtained in the Chronosequence Survey (carried out under the first phase of this work).
25. According to the Countryside Vegetation System, there are a large number of vegetation types and associated species to be found in and around land treated for bracken control. The impact of bracken control on these sites is dependent on a variety of environmental variables.
26. Successful modelling of these processes is possible using unimodal response models. Comprehensive predictive models require much observational data.

ASSESSMENT OF EXISTING MODELS *BRACON* AND *REBRA*

27. Further development of the *BRACON* model requires further sampling of the rhizomes. In a complementary study the model was shown to provide good general predictability, though it is apparent that regional variation is greater than originally expected.
28. *REBRA* is currently unsatisfactory, as it requires incorporating many site-specific characteristics. This work can proceed with further input from the survey data collection proposed for 1999 *et seq*.

GUIDELINES TO MANAGERS

29. Updated guidelines have been included in the Annex to the Scientific Report (Appendix 10.1).

COMPLEMENTARY STUDIES

30. The multivariate analytic technique known as variation partitioning has been used on data from the experimental work. It has consequently been shown that treatment effects are site specific and show much variation. Vigorous bracken is affected much less by treatments.
31. A long-term experiment at Cavenham Heath demonstrated the adverse effect of extraneous factors on heather establishment. These included spatial variables, climate, disturbance and nitrogen pollution in complex interactions.
32. Soil seed-bank trials have been set up to study certain of the ongoing experimental sites. Interim results demonstrate large differences between sites of similar vegetation types. Such studies will assist in the interpretation of vegetation responses to control treatments.
33. The long-term experimental results are beginning to allow interpretation in terms of current vegetation dynamics theories.

POTENTIAL APPLICATIONS

34. A decision support system has been proposed. The model would be of value to policy makers, estate managers and researchers.

FUTURE PRIORITIES

35. Continuation of the bracken control /vegetation restoration, and rate and control of front spread experiments for a further five years will enable further follow-up treatment. A long-term perspective will allow much better appreciation of incidental and long-term environmental changes.
36. Completion of the rhizome sampling exercise. In addition to providing valuable information on the treatment effects on rhizomes, this will provide information for re-parameterisation of *BRACON* to more effectively address site-wise and regional variation.
37. Further work on the Chronosequence Survey is required for establishment and validation of effective vegetation development models, such as *REBRA* . This will include additional survey work on new sites and those already visited. An exercise to follow a new set of sites through spraying and over the following years will be undertaken.

Section 5 : Scientific report

SCIENTIFIC REPORT

1 INTRODUCTION

The aim of this research is to develop integrated techniques to control bracken and restore upland vegetation types, which have both agricultural value and a greater conservation interest. The results reported here are taken from a large Chronosequence study and a series of 11 experiments, which have been running for five or six years. A long time period is needed for these studies because of the slow vegetation development in upland situations.

This report is a summary of research carried out. Detailed results and conclusions can be found in the References and Appendices (see ANNEX).

The first phase (1993-1996) of the work was reported to MAFF in 1996 (Le Duc *et al.* 1996; Pakeman & Marrs 1994a) and the results have been, or are in the process of being, published elsewhere (Le Duc *et al.* 1997a; Pakeman *et al.* 1997 & 1998; Appendix 1.1). This report is concerned, mainly, with the second phase (1996-1999). Since the work carried out related to a series of eight practical objectives the report has been divided in relation to those as well as further, related, sections.

2 BRACKEN CONTROL AND VEGETATION RESTORATION

2.1 Methods

The seven Bracken Control and Vegetation Restoration (BCRE) experimental sites are described in Table 2.1. The replicate blocks are 0.4 ha except in the case of number 7 where they are 0.03 ha. Where appropriate the treatments are applied using ATV equipment, thus necessitating split-plot experimental designs (Le Duc *et al.* 1997b).

The bracken control treatments, five plus experimental control, under investigation include: cutting, herbicide (Asulox) spraying, and combinations of cutting and spraying. The control treatments are identical at all sites except number 7, having cutting twice per year only.

The vegetation restoration treatments are site specific as shown in Table 2.2. An experimental control is again included.

Table 2.1 Bracken control and vegetation restoration experiments

Experiment	Region	Altitude (m)	Start Date	Blocks
1	Cheviot Hills	325	1993	2
2	Cheviot Hills	285	1994	2
3	North Peak	290	1993	3
4	Carneddau	350	1993	3
5	Cannock Chase	145	1993	2
6	Cannock Chase	165	1993	2
7	Cannock Chase	175	1995	2

Table 2.2 Vegetation restoration treatments

Treatment	Sites
Grass seeding	1,2,4
Calluna seeding	3,7
Stock fencing	3
Fertilizer	4,5,6
Harrowing	5,6
Litter burning	7
Weed wiping	1,6
Spot spraying	4

2.2 Results

As these experiments are ongoing the analyses are updated regularly. Results were summarized in 1997 (Le Duc *et al.* 1997b). The results for Experiments 1 and 2 were reported in detail in a platform presentation in 1998 (Appendix 2.1). A poster, given at the 2nd International Conference on Restoration Ecology, Groningen, The Netherlands, 1998, presented the current data for Experiment 3 (Appendix 2.2). Finally, a platform presentation (1998) covering Experiments 5 to 7 is covered by Appendix 2.3. Two additional sets of results are discussed below.

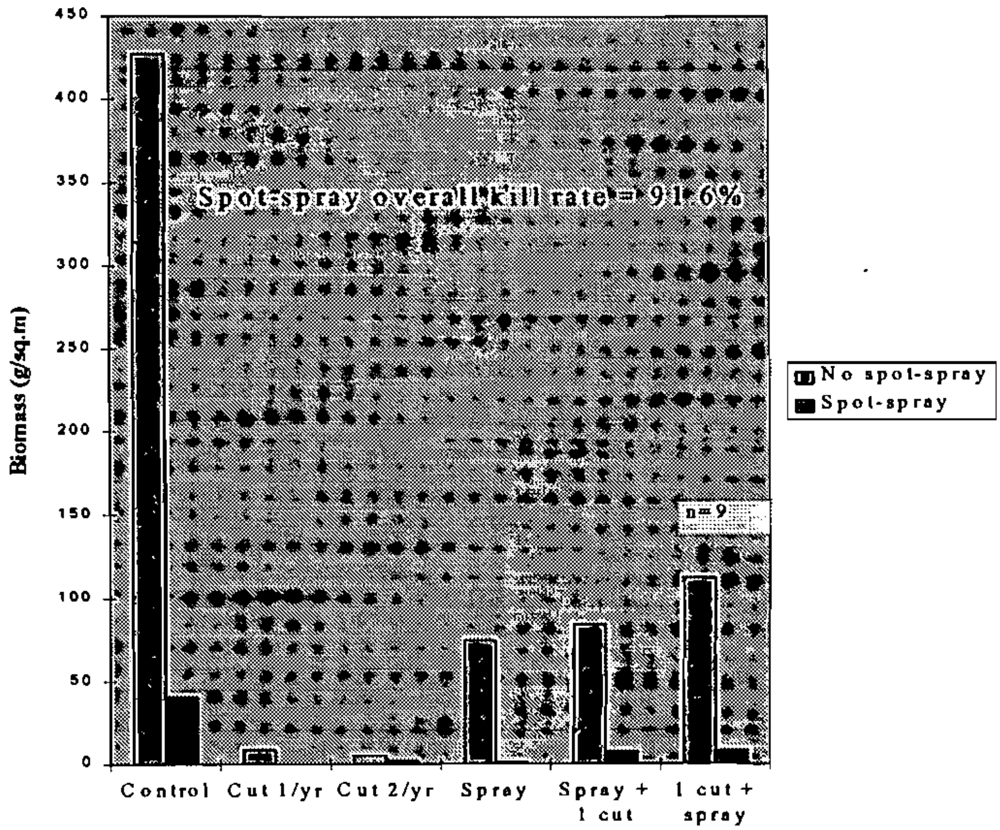


Figure 2.1. Experiment 4, 1998. The impact on frond biomass of spot-spraying with asulam. The result one year after application is shown.

Experiment 4 was subjected to major changes in 1997 when the design was upgraded from split-plot to split-splitplot to accommodate an assessment of the effect of re-treatement by spot-spraying with asulam. The result is summarized in Fig. 2.1.

The graph clearly shows bracken biomass beginning to return to plots originally sprayed in 1993 or 1994 and the benefit that spot spraying brings in remedying this deterioration. Note that the cut treatments continue to show good control, even without spot-spraying.

Long-term cutting is generally seen to produce a good bracken control effect. This is demonstrated by a comparison of all treatments on frond density through time at Experiment 1 (Fig. 2.2). The figure also demonstrates the effect of further herbicide treatment by weed-wiping. Although the plots subject to a single spray only (1993) were seen to be recovering strongly in 1996, after weed-wiping that year there was a

return to a good level of control the following year.

The impact of the weather can be seen in Fig. 2.2. The long hot summer of 1995 produced a peak frond density for untreated plots. This was followed in 1996 by increased bracken performance in the treated plots. Continued cutting treatment and weed-wiping reversed this effect in the following years. Finally, the record wet summer of 1998 led to a poor bracken performance.

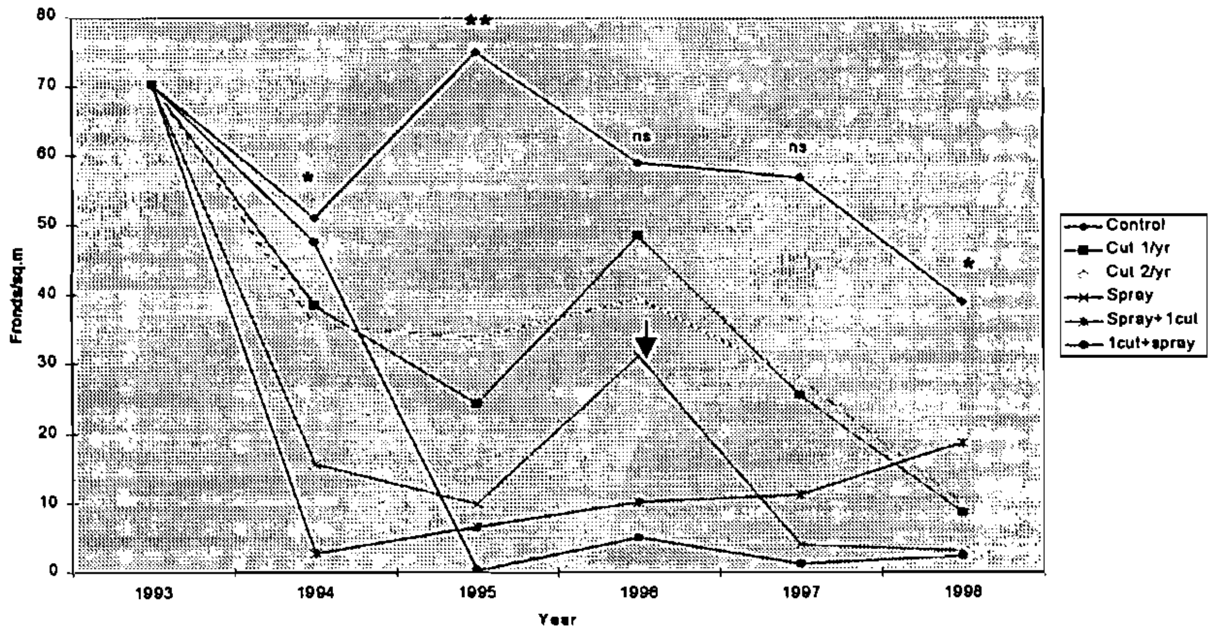


Figure 2.2. Experiment 1, Cheviot Hills. The impact of bracken control treatments on frond density through time. Weed-wiping was applied in 1996, as a follow-up treatment, to those plots treated originally as 'Spray' only (the appropriate curve is arrowed to indicate the time of application). Conventional statistical notation used.

2.3 Conclusions

Bracken control

Spraying with asulam is an effective short term measure for controlling bracken. Given accessible terrain, then a single cut either a year before or one after spraying produces the best result.

For longer-term control follow-up spot-spraying yields a good effect, but it is probably necessary to repeat this at regular intervals of about 4-6 years depending on the local vigour of the bracken stand. Weed wiping is effective also, but not as good as spot-spraying.

Cutting, though initially slow, is very effective in the longer term. At the higher altitude, low productivity, sites one cut per year may be adequate. Two cuts, or more, may be needed where the bracken productivity is high.

Bracken productivity is site-dependent and thus the response to treatments varies over quite short distances (Experiments 1 and 2, reported on in Appendix 2.1, are only 1.5km apart). Thus each site requires careful attention for optimum control.

Vegetation restoration

Restoration of *Calluna* heath can be initiated by the application of *Calluna* brash or litter collected from under a mature *Calluna* stand. Establishment is very slow (Le Duc et al. 1997b) and dependent on the weather and, possibly, atmospheric pollutants (Appendix 11.1).

When *Calluna* seeding treatments are combined with spraying control treatments there is a danger of invasion by weedy species and/or *Deschampsia flexuosa* hindering good establishment. These problems may be avoided by the use of cutting regimes. Low intensity sheep grazing may be appropriate instead of cutting.

Some component species of upland grassland are more shade tolerant than heath species. Often many of the typical species of the former vegetation are surviving, though at significantly reduced abundance, beneath the bracken canopy.

Nevertheless removal of the bracken canopy does not necessarily mean a rapid return to the original vegetation type. There is a danger of establishment of stand-forming or weedy species where vegetation structure has been weakened. Thus, depending variously on location, fertility and history, stands of *Nardus stricta*, *Holcus mollis*, *Deschampsia flexuosa*, *Juncus* spp., *Luzula sylvatica*, *Molinia caerulea*, *Rumex acetosella*, *Urtica dioica*, or *Digitalis purpurea* may develop.

Where bare ground remains after bracken removal there is a high risk of soil erosion (Appendix 7.1), especially on steeper slopes. It is well known that this can be exacerbated by the presence of grazing animals. Thus grazing should be restricted for some time after initiation of bracken control treatment.

Good quality grassland can be encouraged by disturbance of any remaining bracken litter and the application of grass seed mix. At upland sites adequate litter disturbance may be achieved using a flail cutter for frond cutting. On low fertility sites, for sheep grazing, low input of fertilizer may be appropriate.

3 **REMEDIAL TREATMENT OF SPRAYED SITES** (see also Appendix 3.1)

3.1 Two experiments were initiated in 1993 to investigate cost-effective methods to re-establish heather dominated vegetation on land previously subject to bracken control and vegetation development was very slow or dominated by non-target species.

3.2 At Wetherhouse Moor (North York Moors, NGR 4550 4940), the site had been sprayed in 1990, the loose litter had disappeared rapidly and a vegetation dominated by *Rumex acetosella* had developed under relatively high, sheep stocking levels. Combinations of ± grazing, ± fertilizer addition, ± litter disturbance, and ± heather seed addition (with and without a nurse crop) were used in a split block design, with grazing as the main plot factor. Heather growth was slow, but the results clearly show that to get good establishment of heather, then grazing needs to be controlled, litter has to be removed and a seed source added (Fig. 3.1). The nurse crop actually reduced establishment. Bracken recovery was faster where protected from grazing.

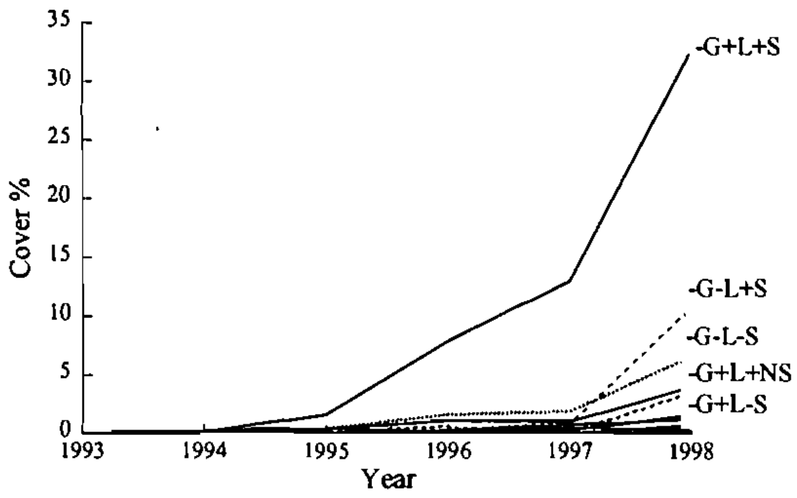


Figure 3.1. Effects of treatment on heather cover at Wetherhouse Moor. G = grazing, L = litter disturbance, S = heather seed, NS = heather seed and nurse crop.

3.3 At Hordron Edge (Derbyshire, NGR 4214 3868), the site had been sprayed in 1991, but large areas of deep litter remained with almost no vegetation cover. Grazing was light. Combinations of ± bracken follow-up treatment, ± fertilizer, ± litter disturbance and ± heather seed addition were used in a split block design with bracken follow up as the main plot factor. Heather growth was slower than at Wetherhouse Moor. In five years, the best treatment only reached 6 % cover, though this was half the overall cover.

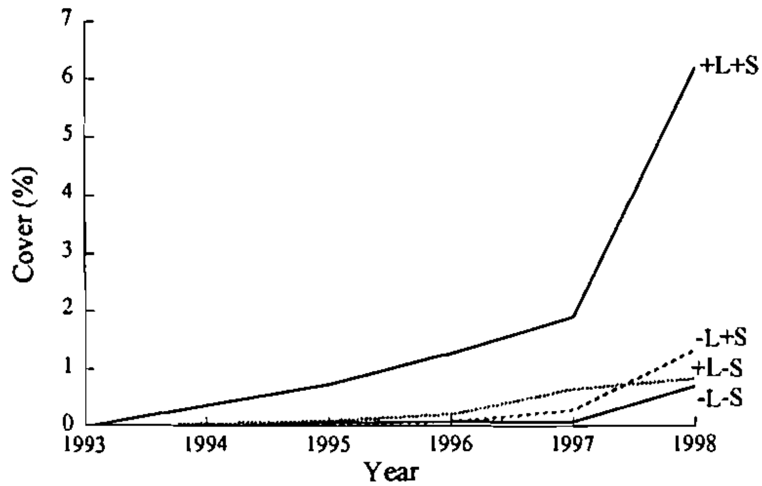


Figure 3.2. Effects of treatment on heather cover at Hordron Edge. L = litter disturbance, S = heather seed addition.

3.4 Conclusions: Where grazing pressures are high, then it would appear that heather re-establishment needs protection from grazing, as well as litter disturbance and a source of propagules. Where sheep activity is low, then litter disturbance and seed addition are the only initial treatments necessary. However, in the long-term (beyond the five years of this experiment) continued bracken suppression will also prove necessary.

4 CONTROL OF BRACKEN SPREAD

4.1 Two experiments were set up to investigate the effects of control measures on the rate of encroachment of bracken into heather moorland.

4.2 The first experiment (Levisham Moor, North York Moors, NGR 4836 4941) was designed to analyse effects of two different treatments, cutting and asulam application.

Over the five years between the initial and final measurements, the untreated bracken fronts spread linearly by 2.4 m, a rate of 0.49 m yr^{-1}. Where control was by cutting, encroachment totalled only 0.84 m over the same period (0.17 m yr^{-1}), a difference of 1.58 m. The effects of spraying with asulam are less easy to compare as apparent encroachment contains an element of recovery. However, the sprayed front was 3.48 m behind the unsprayed one in 1998, despite apparently spreading at 0.5 m yr^{-1} in the years following control. Apparently sprayed bracken would never catch up the effects of the spraying if rates during the study stayed constant.

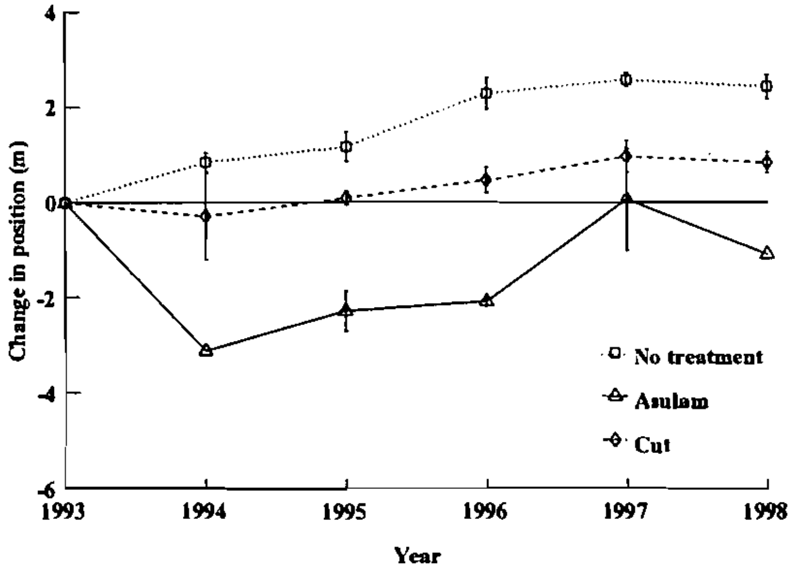
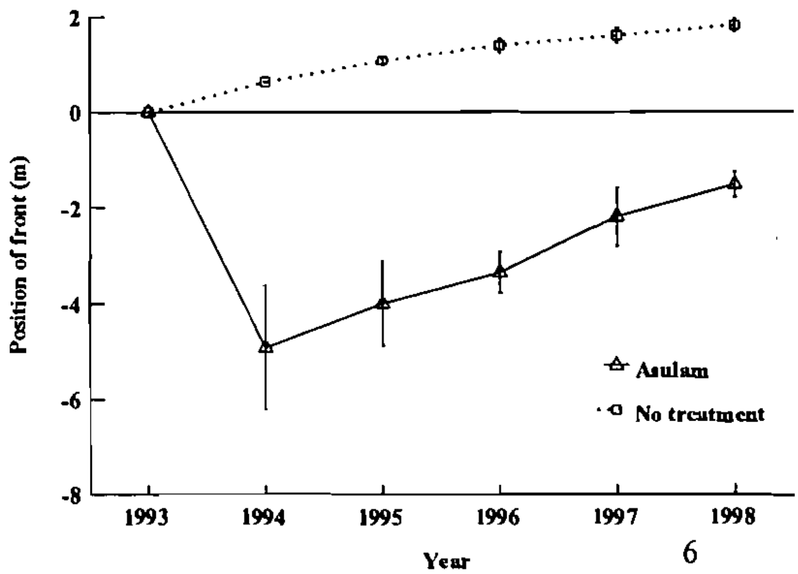


Figure 4.1. Effects of treatment on the relative front position at Levisham Moor from 1993 to 1998.

The experiment was also set up to show effects of control on frond and rhizome biomass. These show similar patterns to those of overall encroachment.

4.3 A similar picture was apparent at the second experimental site (Ramsley Moor, Derbyshire, NGR 4289 3750). This experiment was designed to investigate the effects of asulam application and the interaction between bracken encroachment and vegetation change.

Unsprayed bracken encroached a distance of 1.82



m between 1993 and 1998 (0.36 m yr^{-1}). The initial effects of spraying were more severe at this site, but subsequent regeneration was faster (0.85 m yr^{-1}). Sprayed bracken would catch up unsprayed bracken within 12 years at current rates. Encroaching bracken also reduced the cover of other species, in particular heather, but where bracken was controlled, heather cover could be re-established by litter disturbance and seed addition.

Bracken appears to be able to encroach into heather moorland at a substantial rate when unchecked. The rates at this site are similar to rates observed elsewhere (see Pakeman & Hay, 1995). However, both cutting and asulam application appear capable of reducing this rate of spread. Cutting reduced encroachment rate by more than 60 %, whilst with asulam the picture was less clear. However, use of asulam certainly 'buys time' that may be used profitably for more intensive bracken control elsewhere.

5 EXPERIMENTAL ASSESSMENT OF FOLLOW-UP TREATMENTS

5.1 Introduction

The treatments described here are those applied to the BCRE experiments (Section 2). Follow-up treatments applied to other experiments are described in the appropriate Sections (3 & 4).

5.2 Methods

The treatments and application details are described in Table 5.1.

Table 5.1 Follow-up treatments applied to the bracken control and vegetation restoration experiments.

Experiment	Follow-up treatment	Year	Experimental level
1	Weed-wiping[1]	1996	Plot (only on 'Spray' plots)
4	Spot-spraying[2]	1997	Sub-subplot
5	Fertilizer application[3]	1996	Sub-plot (repeat of initial treatment)
6	Weed-wiping[1]	1996	Plot (only on 'Spray' plots)

NOTES:

1. Weed-wiping carried out, 1st week of September, using a Rotowiper by Bissot Engineering International Ltd. with asulam.
2. Spot-spraying was applied by a knapsack with asulam dose rate equivalent to 4.4kg active ingredient.ha^{-1}.
3. The fertilizer used was ENMAG at 150kg.ha^{-1} applied at the beginning of June.

5.3 Results

The effects of spot-spraying and weed-wiping have already been demonstrated in Figs. 2.1 and 2.2 respectively. Spot-spraying was seen to produce an overall frond kill rate 91.6% which was similar to the first asulam application. It was seen to have a substantial effect when combined with any of the other treatments.

At Experiment 1 weed-wiping was shown to reverse the effect of the warm summer of 1995 by returning frond productivity to a level comparable with other treatments using herbicide (Fig. 2.2). Experiment 6 also produced an appreciable response (Appendix 2.3, figures on pages 9 & 11). Whereas frond biomass, for the herbicide combined with 1 cut regimes (treatments 4 & 5), increases considerable between 1996 and 1997, this trend is reversed for treatment 3, the one with weed-wiping in 1996.

The situation with fertilizer application is not so clear. Site 5 probably has the most productive bracken of any of the experiments. This makes the impact on other vegetation difficult to elicit. As demonstrated using variation partitioning, treatment impacts were quite small there in 1996 and 1997 (Appendix 2.3, pages 27-30). However it does seem that bracken's performance is significantly enhanced by the combination of cutting twice a year, litter disturbance by harrowing and the application of fertilizer (Appendix 2.3, page 20).

5.4 Conclusions

Weed-wiping is an effective though not very practical method of follow-up herbicide application to bracken. The equipment used was not robust enough for the conditions on site. Poor ground clearance was also a problem. Nevertheless a measurable impact on bracken performance was made.

Spot-spraying is as effective as the initial application of herbicide. It can be usefully applied in combination with any other treatment methods. The main drawback is the hard physical nature of the work in difficult terrain.

Fertilizer application may result in increased bracken vigor. It could be that the benefits for vegetation restoration might outweigh that effect where bracken is both less vigorous and well controlled.

6 TREATMENT EFFECTS ON BRACKEN RHIZOMES

6.1 Introduction

This project applies to all BCRE experiments (Section 2). However due to the record wet weather of the summer and autumn of 1998 it was only possible to extract the rhizomes from four of the seven experimental sites. As the month of October progressed the rhizome pits increasingly filled with water and then mud. It is intended that the three remaining experiments be sampled at a later date (see Section 13).

6.2 Methods

As with all quadrating exercises on these experiments the sampling locations were selected using random co-ordinates on 1-m grids within each experimental plot. The rhizome pit locations were 0.5 x 0.5 m squares concentric with the 1-m grid cells. Pits were dug deep enough to ensure extraction of effectively all the rhizome material. Pit depths varied down to about 0.5 m for Experiment 4 and about 1.0 m for Experiments 5-7.

Quality was assured firstly by suitable supervision. Secondly pit size was checked regularly with two quadrats acting as gauges. The first (51 x 51 cm internal dimension) was used as a check on maximum size; the second (49 x 49 cm external) was required to pass right down the finished hole.

At Experiment 4 (a split-split plot experiment) one pit was dug in every experimental plot (108 in total). Experiments 5 and 6 (split-plot experiments) comprise 36 experimental plots and each had two rhizome pits. Experiment 7 (split-split plot with 32 plots) had one pit per plot. Thus 284 pits were dug in total.

6.3 Results

The results for rhizome biomass at Experiment 4 are summarized in Fig. 6.1. All treatments seem to have reduced the untreated rhizome biomass, around 4 $kg.m^{-2}$, by at least 50% in the five years of treatment. Although the treatment effects are not significantly different it appears that cutting twice per year and herbicide application followed by a cut in the following year have been most successful.

Experimental sites, sampled to date, are compared in Fig. 6.2. All treatments have been included in the figure. The result shows that Experiments 5, 6 and 7, all within about 4 km of each other, have similar rhizome biomass, whereas that for site 4, in the Carneddau, is about half of that value.

6.4 Conclusions

The bracken control treatments used in these experiments have a significant effect on rhizome biomass. Each reduces the biomass by 50% or more in five years.

Unlike frond biomass, rhizome biomass is fairly constant at a regional scale. However different biogeographic regions can have significantly different amounts of rhizomes.

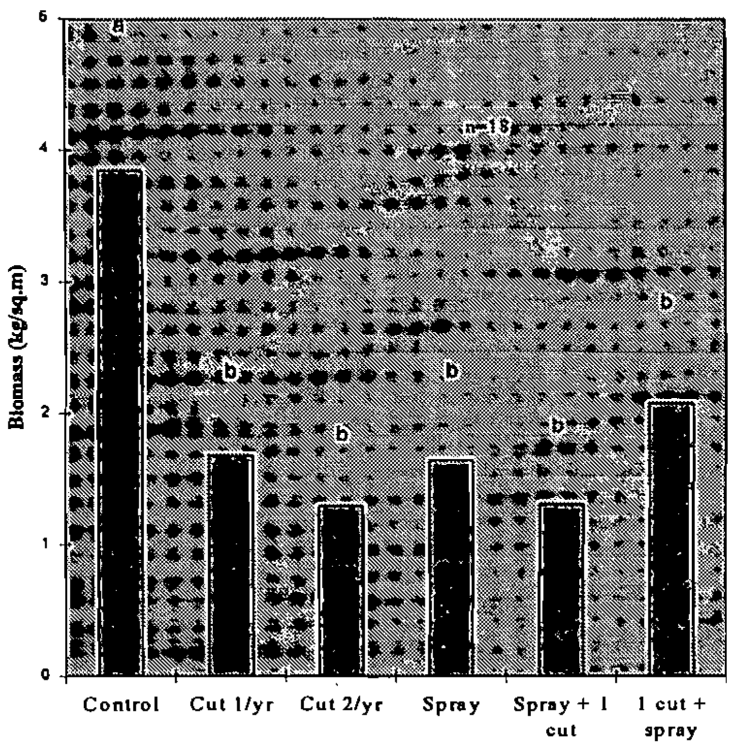


Figure 6.1. Experiment 4, 1998. Rhizome biomass per bracken control treatment.

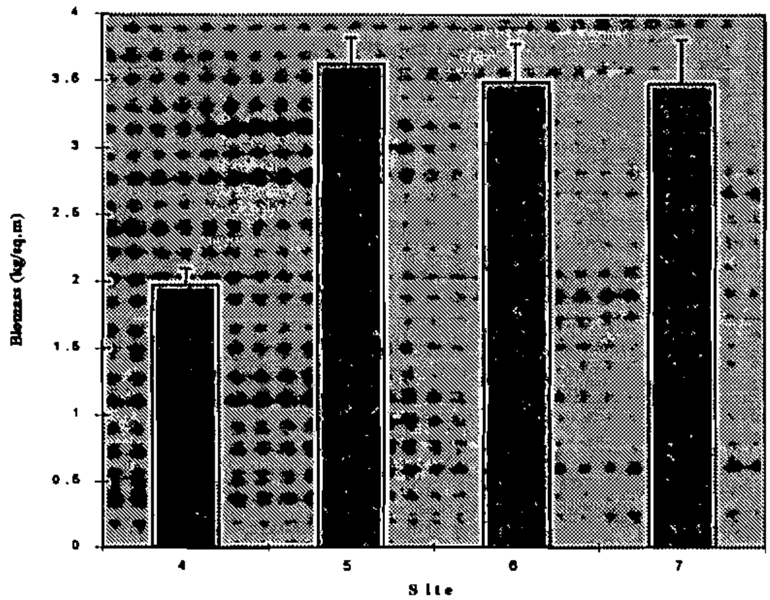


Figure 6.2. Experimental sites compared by rhizome biomass. All treaments included.

7 MOORLAND VEGETATION SUCCESSION AFTER BRACKEN CONTROL WITH ASULAM

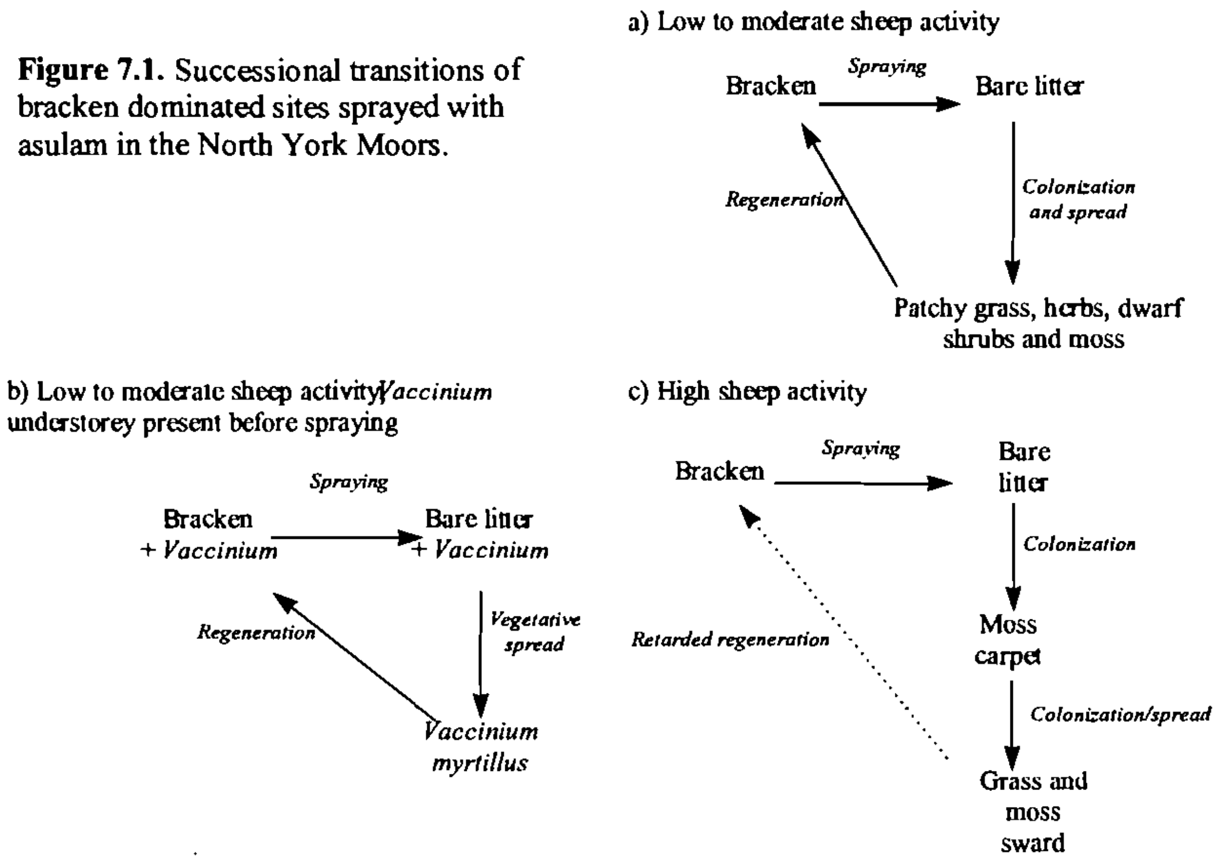
A range of moorland sites in the North York Moors, where bracken control with the herbicide asulam had been carried out were surveyed in 1990 and 1991 (Pakeman & Marrs, 1992). These were resurveyed in 1994 (Pakeman, Le Duc & Marrs, 1997). The trajectory of vegetation change at each site has been analyzed using a range of techniques.

Vegetation change after spraying appears to depend on three things - the species present at the time of control, the initial effectiveness of treatment and the amount of subsequent disturbance (mainly by sheep). Where grazing pressure was low, there was little invasion or spread of plants, except on sites with an initial moderate cover of *Vaccinium myrtillus*. Where high sheep activity disturbed the litter layer, invasion by the moss *Campylopus introflexus* characteristically occurred, followed by an increase in dominance by grasses, especially *Deschampsia flexuosa*. Where grazing pressure was high enough, it appeared that bracken regeneration was slowed, otherwise the bracken canopy and the stand recovered. However, in the timescale of the study, sufficient variety and cover of other species remained after the canopy regenerated, to prevent the complete progression to vegetation characteristic of untreated areas.

A range of successional trajectories can be hypothesised and are shown in Fig. 7.1. However, it must be stressed that these trajectories may only be applicable in the North York Moors and in areas with similar vegetation and climate, e.g. south and north Pennines.

However, the main conclusion to arise from this study was that re-establishment of heather dominated moorland vegetation appeared to be a rare event, and that to achieve this goal, some form of active management would be necessary.

Figure 7.1. Successional transitions of bracken dominated sites sprayed with asulam in the North York Moors.



8 POST-CONTROL VEGETATION DEVELOPMENT MODELS

8.1 Introduction

This work has evolved from the predictive modelling work already published (Pakeman *et al.* 1995). That work was based on biogeographically limited observations (e.g. Pakeman & Marrs 1992).

During the first phase of this project (1993-1996) an extensive survey of sprayed bracken lands was carried out, the Chronosequence Survey. One of its objectives was to amass field data that enabled verification and extension of the modelling. The results from the survey have been published (Le Duc *et al.* 1997a; Pakeman *et al.* 1998) or are in press (Appendix 1.1).

8.2 Methods

The methods used involved the use of the Countryside Vegetation System – part of the ECOFACT programme (Bunce *et al.* 1999) - for classification of the survey data at the quadrat level. This was followed by species unimodal response modelling using the HOF system (Huisman *et al.* 1993) on the resulting data sub-sets. The work is described in more detail in Appendix 8.1 with particular reference to montane heather moorland.

8.3 Results

A general description of the results is presented in Appendix 8.1. As demonstrated there, the vegetation response is highly complex and dependent on a range of environmental variables.

8.4 Conclusions

As demonstrated by this work, there are methods available that enable the development of models of species' response from survey data.

Because of the ubiquity of bracken, and the large number of associated vegetation types and component species, such data sets must be large and geographical diverse.

Space-for-time replacement analysis is dependent on a large number of survey sites. Validation should involve return visits to a significant number of sites.

9 ASSESSMENT OF EXISTING MODELS *BRACON* AND *REBRA*

9.1 *BRACON*

The bracken growth model *BRACON* (Pakeman *et al.*1994) was tested extensively on a geographically diverse set of experiments (Paterson *et al.* 1997a). The model was shown to be adequate but it was recommended that longer-term studies be undertaken, together with further investigations of rhizomes and frond regrowth.

This exercise has been delayed because of the inability to complete the rhizome response exercise (Section 6) as scheduled. When the data are finally available this assessment will be completed.

9.2 *REBRA*

Work on the computer model for re-vegetation after bracken control, REBRA (Pakeman *et al.* 1995), is closely related to that described in Section 8. The first stage is to produce sets of species response models developed from field data. As concluded in Section 8, further progress is dependent on validation of existing species response models described in Appendix 8.1.

10 GUIDELINES TO MANAGERS

These were originally published in 1994 along with a literature review (Pakeman & Marrs 1994a). They were subsequently revised and formed part of the final report for the first phase of this project (Le Duc *et al.* 1996).Once again they have been revised and expanded, particularly to include more information on vegetation restoration (Appendix 10.1).

11 COMPLEMENTARY STUDIES

11.1 Introduction

During the course of the bracken project other studies have been carried out, by this group, which relate directly to it and inform its approach and development. These are described briefly below.

11.2 Analytic methods

The experimental and survey work carried out as part of the bracken project produces large, multivariate sets of data. Accordingly multivariate analytic techniques (e.g. ter Braak 1987) are commonly used and the results reported (e.g. Appendix 8.1). Variation in such sets of data can be partitioned between sets of environmental variables and that of unknown origin (Borcard *et al.* 1992).

We have used this approach successfully with several data sets (Appendices 2.1, 2.3 & 11.1). It has helped to reveal the extent of treatment effect on vegetation change.

11.3 Associated experiments

These comprise several pieces of allied work funded by in-house support and other partners.

The modelling work referred to earlier is based on experimental work performed near Thetford (Pakeman & Marrs 1994b). A number of experiments were undertaken over a wide geographical range, partially to evaluate the *BRACON* model (Paterson *et al.* 1997b).

A long–term experiment, running from 1978 to 1996, at Cavenham Heath, Suffolk has produced a series of publications (Lowday & Marrs 1992a & b; Marrs & Lowday 1992; Marrs *et al.* 1992; Marrs *et al.* 1993; Marrs *et al.* 1998a & b; Marrs *et al.* 1999). A further publication, the ninth in this series, is given as Appendix 11.1. That paper addresses the important issue of succession following control of bracken and has employed multivariate analytic tools to explore some aspects of community dynamics. It discusses the role of weather and atmospheric pollution in vegetation change.

11.4 Soil seed bank

During 1998 it became possible, through a British Council Link Programme with the Regional Plant Resources Centre, Orissa, India, on vegetation restoration of mining spoil, to do some soil seed bank studies of certain experimental sites. Those chosen were Experiments 1, 2, 5, 6 & 7 from the BCRE study. The soils were collected in the spring of 1998 and will continue to be studied through the spring of this year. Preliminary results are shown in Table 11.1. Results show big differences between closely matched pairs of sites, 1 and 2, and 6 & 7.

These studies will not be complete until the end of May 1999, when the flush of seeds in the second year will be assessed. This will give a good picture of the seed bank.

Other seed-bank studies have been published by our team (Pakeman & Hay 1996) in which an assessment of seed-bank change across bracken fronts at

Cavenham Heath (Suffolk), Ramsley (Peak District), and Levisham (North York Moors) were made.

Table 11.1 Bracken Control and Vegetation Restoration Experiments, 1998: Soil seed-bank trials. Tables show the total number of seedlings and sporelings emerging in first year. There were 72 samples from each of sites 1 and 2, 108 from sites 5 and 6, and 32 from experiment 7. The soil samples were 28 cm^2 by 7 cm deep.

SITE 1 (20 spp.)	
Species	**No.**
Dryopteris filix-mas	195
Agrostis capillaris	119
Carex sp.	111
Agrostis vinealis	60
Galium saxatile	53
Juncus effusus	46
Dryopteris dilata	18
Anthoxanthum odoratum	10
Nardus stricta	7
Luzula sp.	5
Agostis canina	4
Holcus lanatus	4
Deschampsia flexuosa	3
Poa trivialis	2
Poa pratensis	2
Erica tetralix	1
Deschampsia cespitosa	1
Urtica dioica	1
Potentilla erecta	1
Blechnum spicant	1

SITE 2 (25 spp.)	
Species	**No.**
Digitalis purpurea	574
Dryopteris dilata	418
Cirsium palustre	189
Agrostis capillaris	137
Stellaria media	130
Dryopteris filix-mas	91
Juncus effusus	88
Galium saxatile	34
Agrostis vinealis	29
Poa annua	28
Carex sp.	20
Poa trivialis	12
Luzula sp.	10
Poa pratensis	10
Potentilla erecta	9
Deschampsia flexuosa	5
Deschampsia cespitosa	3
Blechnum spicant	3
Anthoxanthum odoratum	2
Epilobium hirsutum	1
Campanula rotundifolia	1
Cerastium fontanum	1
Festuca rubra	1
Juncus articulatus	1
Erica cinerea	1

SITE 5 (10 spp.)	
Species	**No.**
Calluna vulgaris	457
Agrostis capillaris	13
Digitalis purpurea	9
Ulex sp.	7
Betula pubescens	5
Juncus effusus	2
Vaccinium myrtillus	2
Holcus lanatus	1
Carex sp.	1
Rumex acetosella	1

SITE 6 (4 spp.)	
Species	**No.**
Calluna vulgaris	14334
Juncus effusus	6
Vaccinium myrtillus	2
Betula pubescens	1

11.5 Soil chemistry

A large number of the sites visited during the Chronosequence Survey had soil samples taken. These have been analysed for chemical composition and a preliminary analysis has been published (Le Duc *et al.*1997a).

Extensive soil chemical analysis was carried out in 1997/98 for the BCRE Experiment 3, North Peak. These data have yet to complete analysis.

11.6 Theoretical aspects

Community structure and function are major theoretical issues in plant ecology. Structural measures, such as diversity, evenness and rank-abundance, are increasingly seen to be fundamental in ecosystem studies (Tokeshi 1993; Hill 1997). Theories on the relationship between biodiversity and ecosystem functioning have recently become controversial (Marrs *et al.* 1996; Naeem *et al.* 1996; Hodgson *et al.* 1998). Experimental evidence is becoming available through this project that allows contributions to made in these areas (Appendices 11.1 & 11.2).

12 POTENTIAL APPLICATIONS

12.1 Decision support system

The bracken projects have amassed much of the information required to develop a decision support system. Such a system might be modular, as shown in Fig. 12.1, using a mix of model types, including simulation models (e.g. BRACON & REBRA), expert systems, artificial neural networks and mathematical models.

The model would be of value to policy makers, estate managers and researchers. Its modular nature would aid in validation and updating.

13 FUTURE PLANS

13.1 Continuation of bracken control/vegetation restoration experimental work (1999-2004): *Calluna vulgaris* is particularly slow to develop, nevertheless heather moorland is developing on appropriate sites. This progress must be viewed against a background of bracken recovery following herbicide treatments. Therefore the rational series of follow-up treatments, started in 1996, will be continued. The monitoring program, established in 1993, will continue.

13.2 In addition to the standard twice-yearly experimental monitoring, rhizome biomass measurement will be carried out in 1999 at the three experiments not yet sampled. Rhizome samples will be collected from the sites at North Peak (one experiment) and Sourhope (two experiments) together with a sub-sample from the experiment on the Carneddau Estate (previously sampled in 1998) to serve as a chronosequential cross-check.

13.3 Experiments set up to monitor the rate of spread of bracken fronts, and methods of control, will be continued. A realistic time period (1999-2004) that takes account of slow and erratic vegetation processes is required.

13.4 Data from the Chronosequence Survey work (1994-95) have provided much important information leading to a series of useful models. These need to tested against an independent data set. A further study is to be carried out with several objectives. Trends will be verified by re-visits to a sample of the original sites (2000 - 2002). A series of additional sites will be surveyed to provide the test data-set (2000-2002). A third set of sites, not yet sprayed, will be surveyed in 1999 & 2000. After spraying these will be monitored annually (2000-2004) thus yielding much model-validation detail for the first five years, that period normally allowed prior to a decision on follow-up spraying.

13.5 Development of predictive models (1999-2004): Data from the experimental work and the chronosequence survey studies need to be drawn together into a series of useful predictve models. This will be done in conjunction with further validation and re-parameterization of the existing bracken growth and vegetation succession models.

Figure 12.1 A decision support system for bracken control