CEE review 04-001

EFFECTIVENESS OF CURRENT METHODS FOR THE CONTROL OF BRACKEN (PTERIDIUM AQUILINUM)

Systematic Review

STEWART, G., TYLER , C. & PULLIN, A.S.

Centre for Evidence-Based Conservation - School of Biosciences - University of Birmingham – Edgbaston – B15 2TT - UK

Correspondence: g.b.stewart@bham.ac.uk
Telephone: 0121 4146873

Final review posted on website: 2005

Cite as: Stewart, G.B., Tyler, C. & Pullin, A.S. 2005. Effectiveness of current methods for the Control of Bracken (*Pteridium aquilinum*). CEE review 04-001 (SR3). Collaboration for Environmental Evidence: www.environmentalevidence.org/SR3.html.

CENTRE FOR EVIDENCE-BASED CONSERVATION

SYSTEMATIC REVIEW NO. 3:
Effectiveness of current methods for the Control of Bracken (*Pteridium aquilinum*)

REVIEW REPORT

LEAD REVIEWER: Dr. Gavin Stewart

POSTAL ADDRESS: Centre for Evidence-Based Conservation
School of Biosciences
University of Birmingham
Edgbaston
B15 2TT
UK

EMAIL ADDRESS: g.b.stewart@bham.ac.uk
TELEPHONE: +44 (0)121 4144090
FACSIMILE: +44 (0)121 4145925

Stewart, G.B., Tyler, C. & Pullin, A.S. (2005). Effectiveness of current methods for the Control of Bracken (*Pteridium aquilinum*) Systematic Review No. 3. Collaboration for Environmental Evidence.

Summary

Background

Control of bracken (*Pteridium aquilinum*) is a global problem for livestock-based extensive agriculture, conservation, recreation, game management and forestry. Bracken is controlled primarily by application of asulam or by cutting. The success of bracken control may be dependent upon ecological variables (such as habitat type and latitude) and methodological variables (such as number and timing of treatments). We synthesised the available evidence regarding the effectiveness of bracken control interventions in order to identify knowledge-gaps and provide an evidence-base to support decision making where bracken control is a problem.

Objective

The primary objective was to assess evidence on the impact of asulam on bracken abundance and to determine why the impact might vary. A secondary objective was qualitative assessment of the impact of other bracken control interventions on bracken abundance.

Study Inclusion Criteria

Studies were included if they fulfilled the following relevance criteria;

- *Subjects(s)* studied – *Pteridium aquilinum* (except where it occurred in a woodland context).

- *Interventions* – Herbicides, Mowing or cutting, handpulling, rolling, use of livestock (cattle, sheep, ponies) or burning with control of bracken as an objective, and combination of techniques.

- *Outcome(s)* – Any change in the abundance of bracken including frond density, cover, frequency, above or below ground biomass.

- *Comparator* – appropriate controls (e.g. untreated reference areas) or pre-treatment comparators.

- *Type of study* – any primary studies.

Scope of the Search

Five databases (the bracken database, English Nature's "Wildlink", Index to Theses Online, ISI Web of Knowledge and JSTOR) were searched for published and unpublished information using a range of search terms. Bibliographies of retrieved articles were checked for additional relevant references. Subject experts were contacted.

Main results

Over 2995 references were retrieved. These provided 46 relevant data points for meta-analysis of asulam impact, with a further 14 references pertaining to bracken control by other means. Meta-analysis confirmed that asulam application significantly reduces the abundance of bracken. Meta-regression confirmed that the number of applications of asulam has a significant impact on effectiveness, with multiple follow

up treatments necessary for good control. Other variables such as habitat, latitude, timing of application, and concentration of herbicide did not have a significant impact on asulam effectiveness. There was insufficient information regarding other interventions for robust meta-analysis. Qualitative synthesis suggested that cutting could be as effective as asulam application.

Conclusions

Implications for Management

Available evidence suggests that asulam application reduces the abundance of bracken although subsequent regeneration can be rapid. Multiple applications of asulam are more effective than single applications, slowing the speed of recovery. More high quality research and monitoring is required to ensure that current management recommendations are generic rather than site specific, but there is no evidence that they require modification. However, much current control consists of a single application of asulam with no or limited follow up. This is ten times less effective than control with multiple follow up. It is therefore more effective to spray a fifth of a site five times over five years than the whole site once. The former treatment results in decreased bracken abundance across a fifth of the site, whilst the latter treatment may have no effect at all by the fifth year. Qualitative evidence suggests that cutting could be as effective as asulam application, particularly if two cuts are applied within the same growing season, but further work is required for corroboration.

Implications for further research.

Further research is required to fill a number of knowledge gaps regarding the impact of bracken control strategies. There is a lack of head to head comparisons regarding the effectiveness of different control strategies. In particular, long term work comparing cutting and asulam application is required to build on the existing work. There is no robust experimental evidence regarding the impact of rolling on bracken abundance, although the technique is being applied at a small scale on inaccessible ground unsuitable for cutting machinery. Ongoing monitoring of rolling impacts and experimentation on bracken bruising should receive funding to ensure its continuity.

With respect to asulam application, further information is needed on the number of follow up treatments and aftercare required for specified levels of desired control. Complete eradication of bracken using asulam has not yet been demonstrated experimentally, although one study (Spaunton Moor, UK) provides evidence that virtual eradication is possible. Further work is also required regarding the efficacy of different application techniques, as this work suggests that their effectiveness is variable. The impact of many effect modifiers such as habitat, location and land management also require further investigation across multiple sites if generic bracken control strategies are to be validated. Further meta-analysis is ongoing but this should be augmented with the collection of additional data to increase sample sizes and minimise confounding effects.

Future experimental work should give careful consideration to abundance measures. Although, easily measured, frond density is not a good measure of

bracken abundance as it fluctuates rapidly. Rhizome abundance is considered the optimal measure, preferably measured alongside frond biomass.

Further primary studies are an essential component of the required research but further synthesis of large scale information e.g. correlating countryside survey vegetation change data with areas where bracken control has been funded through agri-environment schemes; and monitoring the effectiveness of bracken control where aerial spraying has occurred, could also be valuable tools.

However, some researchers believe that further research on control would necessarily detract from research on other topics; namely the steps needed to regenerate appropriate vegetation after control and also what is causing bracken to spread in the first place. These topics are beyond the scope of the existing review but important questions worthy of further attention.

Background

Bracken (*Pteridium aquilinum*) is a major problem for livestock-based extensive agriculture, conservation, recreation, game management and forestry both in the UK and further afield (Pakeman *et al.* 2001). In the UK, bracken is a cause of concern to the Royal Society for Protection of Birds (RSPB), English Nature, and other conservation organisations as it is a potentially invasive species on all ericaceous heath and acidic grassland including nature reserves. Where bracken is dominant it excludes most specialist heathland/moorland bird species of conservation concern, although there are a few species that may benefit from a certain proportion of bracken e.g. nightjar and whinchat. Conservation managers therefore usually wish to reduce the abundance of bracken and restore either dwarf-shrub dominated heath or acid grassland (Pakeman and Marrs 1994a). Conversely, on occasion, bracken is considered valuable in conservation terms providing refugia for woodland ground flora or habitat for fritillary butterflies. However, the optimum levels of bracken control are rarely, if ever, specified in these situations (Pakeman *et al.* 2000).

Bracken is controlled in Great Britain, primarily by either application of the herbicide asulam or cutting (Pakeman *et al.* 2000). Accurate figures for area covered by aerial spraying of asulam in the UK are maintained (Wardman and Thomas 1999, 2003). Between 1980 and 1988, 845km^2 was sprayed, representing 20% of the land area of dense bracken (Barr *et al.* 1993) at a cost of £12M (Pakeman *et al.* 2001). In 1998/99, 4390 km^2 equivalent to 1.9 % of the land area of Great Britain consisted of dense bracken in open ground (Haines-Young *et al.* 2000). Over the period 1980 to 2002, asulam was applied to bracken over a total area of 1057 km^2, representing 24 % of the area of bracken habitat recorded in 1998/99 (Haines-Young *et al.* 2000), with the majority applied during the 1990s (Pakeman *et al.* in press). Thus estimates, regarding the proportion of bracken extent and sprayed appear roughly consistent through the decades since the 1980s.

Currently Countryside Stewardship grants in England are £70 ha^{-1}, which covers 40 % of the cost of aerial spraying (Department for Environment, Food and Rural Affairs 2003a; 2003b) and Rural Stewardship in Scotland pays £120 ha^{-1} for the capital costs of starting a spraying programme (Chadwick 2003; Scottish Executive 2003). Thus considerable sums of money continue to be expended on attempts to control bracken across the UK, and the problem of bracken control could increase if upland deintensification is pursued.

Follow up procedures and the exact areas sprayed by non aerial means are less clear, as is the use of other intervention techniques. It has been estimated that the area of bracken control by cutting exceeded the area sprayed approximately sevenfold in the Less Favoured Areas of England and Wales where upland land management is widespread (Pakeman *et al.* 2000, Lawton and Varvarigos 1989).

Other management interventions have been employed to control bracken. Chemical alternatives to asulam have been trialled but only asulam is licensed for aerial spraying (Bayer CropScience 2005). No other chemicals have been adopted with the exception of glyphosate which is less specific than asulam and therefore only used where bracken is one of a number of weeds to control (Pakeman *et al.* 2000).

Mycoherbicides and insect biocontrol options have also been explored but are not used. Crushing using rollers is another more recent alternative mechanical control technique generally used on terrain which might damage a cutter (Pakeman *et al.* 2005). Stock treading and Burning are other land management techniques sometimes employed to crush bracken and disturb litter in the former and remove litter in the latter (Pakeman *et al.* 2005). The choice of management is dependant upon many factors such as cost, terrain, availability of stock, machinery, manpower and knowledge. Organic farming status may preclude the use of chemical control.

There is a large body of literature concerning the effects of management on bracken; e.g. the 'bracken database' contains 1800 papers many of which are relevant to the control of bracken. Numerous conventional reviews exist (Pakeman & Marrs 1994a, 2001, Pakeman & Sangster 2000, Pakeman *et al.* 2000a, 2000b, 2001) which are consistent with current management guidelines (SUP 2001, Pakeman *et al.* 2005). However, no attempts have been made to formally synthesise this information using a systematic review to provide an evidence-based framework to support decision-making as advocated by Pullin and Knight (2001), Pullin *et al.* (2004) and Sutherland *et al.* (2004).

The explicit methods used in this systematic review limit bias through the use of comprehensive searching, specific inclusion criteria and formal assessment of the quality and reliability of the studies retrieved. The use of meta-analysis increases statistical power and thus the precision of estimates of treatment effects providing generic empirical evidence on the impact of asulam on bracken abundance. Meta-regression allows exploration of reasons for heterogeneity in results providing testable hypotheses about ecological or methodological characteristics that may have an impact on the effect of control on bracken abundance. Finally, the review highlights gaps in research evidence identifying needs-led research as a priority for future funding.

Objective

The primary objective was to assess the evidence on the impact of asulam on bracken abundance and to determine why the impact might vary.

A secondary objective was qualitative assessment of the impact of other bracken control interventions on bracken abundance.

Methods

Question formulation

Question formulation was an iterative process involving CEBC and RSPB personnel. Initially, the question was 'what is the impact of various bracken control interventions on bracken abundance, community composition and other outcomes in acid grassland and heathland?' As the review progressed, it became apparent that there was limited high quality information on interventions other than asulam application and outcomes other than bracken abundance, and very few direct head to head comparisons of different management techniques. The review therefore concentrated on the effect of asulam on bracken abundance whilst cataloguing sources of information regarding other interventions.

The consideration of heterogeneity is a critical aspect of systematic review (Bailey 1987, Thompson 1994), allowing the formation of testable hypotheses about ecological or methodological characteristics that may have an impact on the effect of control on bracken abundance. Differences in the characteristics of the populations, interventions and types of outcome can explain apparent differences in the findings of primary studies, thus it is recommended that these factors are specified *a priori*, preferably supported by a scientific rationale (Khan *et al.* 2000). Habitat type, location, soil moisture and time were considered as *a priori p*rimary reasons for heterogeneity in results. Specific intervention related variables were defined as the number of herbicide applications, concentration of herbicide, time of application and method of application. Abundance measure (above or below ground) and land management were final reasons for heterogeneity.

Search strategy

Electronic database and internet searches

The databases searched were:

- the bracken database (http://www.appliedvegetationdynamics.co.uk/database.html)
- English Nature's "Wildlink
- Index to Theses Online
- ISI Web of Knowledge
- JSTOR

Search terms were as follows:

- *Pteridium aquilinum* and Management
- *Pteridium aquilinum* and Control*
- Bracken and Management
- Bracken and Control*

Other searches

The RSPB library was hand searched. In addition, bibliographies of articles accepted for full text viewing, and those in otherwise relevant secondary articles, were searched. We also contacted recognised experts and current practitioners undertaking bracken control to identify possible sources of primary data and to verify the thoroughness of our literature coverage.

Inclusion criteria

Specific inclusion criteria were based on the subject, intervention, outcome and comparator. The criteria were defined before the studies were assessed. They were refined and narrowed in scope prior to data extraction as described in question formulation. The review specific criteria were:

- *Subjects(s)* studied – *Pteridium aquilinum* (except where it occurred in a woodland context, where bracken control has different objectives).

- *Interventions* – Herbicides, mowing or cutting, handpulling, rolling, use of livestock (cattle, sheep, ponies) or burning with control of bracken as an objective and combination of techniques (only information regarding asulam application was extracted for quantitative analysis).

- *Outcome(s)* – Any change in the abundance of bracken including litter (frond density, cover, frequency, above or below ground biomass), change in plant community composition, change in the abundance of any plant or animal species (only information on bracken abundance was extracted).

- *Comparator* – appropriate controls (e.g. untreated reference areas) or pre-treatment comparators.

Relevance assessment

Initial screening of references for relevance using the inclusion criteria was performed by one reviewer (CT), with reference to a second (GBS) in cases of uncertainty. Where there was insufficient information, it was assumed that references were relevant. The same approach was adopted for relevance assessment at full text.

Study quality

Study quality assessment was carried out at full text by critical evaluation of methodology, using a hierarchy of evidence adapted from models of the systematic review process used in medicine and public health (Stevens & Milne 1997, Pullin & Knight 2003). Assessment of selection bias, performance bias and assessment bias was also incorporated in study quality assessment, examining factors likely to confound the observed relationships if they vary unequally in treatment and control groups (Khan *et al.* 2001). The review specific factors were: study design (particularly, randomisation, replication and use of controls), the degree to which baseline conditions were uniform (especially with regard to bracken abundance prior to experimentation), the degree to which heterogeneity within treatment and control arms was balanced, the occurrence of confounding factors, the precision of the outcome measures and size of experimental area. Study quality assessment was performed independently by two reviewers (CT, GBS) with disagreement resolved by consensus. The assessments of study quality are described in the table of included studies (Appendix 1).

Data extraction

Relevant data were extracted by two reviewers (CT, GBS) independently, with subsequent discrepancies resolved by consensus. For the purposes of data extraction, all independent information on the abundance of bracken on treated and comparator sites was extracted, with variance derived from replicate observations. In many instances, different treatments were compared to the same controls in complex factorial designs. In these instances non-independent data were extracted provided the intervention was asulam application e.g. asulam applied in two concentrations at two times of year compared to one untreated control. Where there was a choice of outcome measures, e.g. frond abundance or rhizome biomass, frond abundance was extracted preferentially to maintain independence.

Data synthesis

Qualitative synthesis
Quantitative synthesis of information regarding interventions other than asulam application was considered inappropriate due to the limited number of high quality studies. Qualitative assessment was performed by tabulating information from the studies regarding methodology and the outcome. Where possible, conclusions were drawn.

Meta-analysis
Data synthesis regarding the impact of asulam was achieved through qualitative synthesis, complemented by meta-analysis and meta-regression. Qualitative synthesis consisted of tabulation of study characteristics and outcomes to highlight similarities and differences in key ecological, methodological and outcome measures (Table 1).

Cohen's D effect sizes (Deeks *et al.* 2001) were derived from the treatment and control means, standard deviations and sample sizes. Sensitivity analyses were used to verify the robustness of the effect size estimator.

Data were pooled and combined across studies using DerSimonian and Laird random effects meta-analysis based on standardised mean difference (SMD) (DerSimonian & Laird 1986; Cooper & Hedges 1994). Sensitivity analysis was performed to assess the impact of including non-independent data by combining the greatest possible independent effects and then substituting the smallest and comparing results.

Further sensitivity analyses were performed to assess the impact of including sites with imputed data (Khan *et al.* 2001, Morton *et al.* 2001). Where variance data was unavailable, the largest standard deviation from other studies was doubled, and sample sizes reduced (n = 2) to provide conservative down-weighted variance measures (Wolf & Guevara 2001).

Assessment of heterogeneity and bias
Heterogeneity was assessed by inspection of Forrest plots of the estimated treatment effects from the studies along with their 95% confidence intervals, and by formal tests of homogeneity undertaken prior to each meta-analysis (Thompson and Sharp 1999). Likewise, each meta-analysis was accompanied by a Funnel plot (plots of effect estimates versus the inverse of their standard errors). Asymmetry of the funnel plot may indicate publication bias and other biases related to sample size, though it may also represent a true relationship between trial size and effect size. A formal investigation of the degree of asymmetry was performed using the method proposed by Egger et al. (1997).

Exploration of reasons for heterogeneity

We hypothesised that the effect of asulam on bracken abundance differs according to habitat type, location, soil moisture, abundance measure, land management, length of experiment, number of herbicide applications, concentration of herbicide, time of application, and method of application. The association of these factors (except soil moisture) with estimated effects were examined by performing univariate and multivariate random effects SMD meta-regression in Stata version 8.2 (Stata Corporation, USA) using the program Metareg (Sharp 1998).

Results

Review statistics

Searching retrieved over 2995 unique bibliographic references, of which 233 articles were accepted for full text viewing after initial screening of title and abstract. This was inclusive of articles where there was insufficient information to make a decision without reference to the full texts.

After full text viewing, a further 152 references were excluded as they did not fulfil the inclusion criteria. Of the remaining 87 articles, nine were duplicate publications based on data from the same sites, and 54 did not contain quantitative data. Ten references presented quantitative information regarding the impact of asulam on bracken (Table 1). Multiple data points were extracted from each relevant article and sensitivity analysis was used to explore the impact of independence (see Methods). Fourteen references did not pertain to control by asulam but were relevant to other interventions, e.g. cutting, and were admitted to the review (Tables 2-3, Appendix 2).

Study quality

Sixteen effect sizes were derived using multiple non-independent points with variance measures. These formed subsets of nine independent data points for robust analysis based on high quality randomised controlled trials, although multiple effect sizes were derived from one study site, increasing the potential for bias.

A further 30 effect sizes were derived using multiple non-independent points with imputed variance and sample size. The quality of these data is lower, although in many instances the lack of variance results from the use of least significant difference statistics hence lack of reporting rather than lack of replication (Table 1, Appendix 1).

Lack of reported variance measures and problems of independence were the primary study quality issues. Small sample sizes and pseudoreplication were also problematic. In many instances, baselines were either unreported or were not comparable when they were reported, particularly with respect to initial bracken abundance. Rhizome ingression from out with the treatment area was also inadequately considered in some of the included studies with small plot sizes. The rigour of observations was variable as measured in terms of replication and objectivity (Aappendix 1).

Study characteristics

Of the 46 data points, 40 are based on UK sites, with four from Canada and two from Australia. Sixteen concern UK lowland heath, 16 are based on grass dominated moorland (from only two studies), with a further eight based on *Calluna* dominated moorland. Four are from cultivated blueberry fields with two in an unspecified open habitat.

Information on soil moisture and land management was not presented or was insufficiently detailed to be of utility. Experimental length was variable, with the majority of studies based on one application of asulam and short timescales of <3 years, with one notable study based on three or four asulam applications and a timescale of 18 years (Table 1).

Table 1. The ecological and methodological characteristics, study quality and outcome of the included studies.

Reference	**Characteristics**		**Study quality**	**Outcome: Aggregate unweighted mean difference**
	Ecological	**Methodological**		
Marrs *et al* (1998)	Frond biomass* (g/m^2) assessed over 216 months from 1978 on lowland heath (UK), latitude 52.30°. *Rhizome data is also presented.	3-4 applications at 4.4kg a.i ha-1 in August using a motorised backpack mistblower.	4 data points. Complex factorial experiment looking at the impact of different controls (including asulam) and associated treatment in two replicate blocks (n=2). The impact of asulam applied three times and four times after eighteen years was extracted separately for each replicated block although the control plot represents pooled data; thus extracted data is pseudoreplicated and not independent. This work is one of very few longer term bracken control studies.	Aggregate mean difference of -206.2 (control = 404.2).
Whitehead (1994)	Number of active rhizome buds assessed over 3 months from 1991 on *Calluna* moorland (UK) and *ex situ*, latitude 54.24°.	1 application at 0.16-0.8 kg a.i ha-1 in May (*ex situ*) or July by hand.	8 data points. An ex situ experiment investigates the response of active rhizome buds to three sub-lethal concentrations of asulam (using the same control). The same phenomenon is investigated in the field at five points across replicated Calluna/Pteridium interfaces (using independent controls but not independent points).Both experiments are replicated but have problems of independence. The potential for rhizome ingression/disturbance is problematic as is the short timescale.	Aggregate mean difference of -17.56 (control = 39.37)
Jackson (1981)	Frond density (fronds/100m^2) assessed over 12 months from 1981 on blueberry fields (Canada), latitude 45.04°.	1 application at 1.12-2.24 kg a.i ha-1 in July using a boom sprayer	4 data points. A randomised controlled trial in blueberry bush fields utilising two sites and two herbicide concentrations (The sites are independent but the concentration treatments are compared to the same mean). There is good reporting of baseline which unfortunately was not comparable with respect to bracken abundance and had high variance prior to experimentation. The application of results from such a cultivated system to marginal land bracken control could also be questionable.	Aggregate mean difference of -36.25 (control = 38.25)
Paterson *et al* (1997)	Frond density (fronds/m^2) assessed over 24 months from 1993 on lowland heath (UK), latitude 51.13-56.39°.	1 application at 4.4kg a.i ha-1 in July using a knapsack sprayer.	6 data points. Randomised controlled trials of various treatments (including asulam application) applied at 6 sites with high precision (36 quadrats used to assess each plot) but low replication (n=3) and no baseline reporting. Variance measures are not extractable for treatment and control.	Aggregate mean difference of -21.86 (control = 30.88)
Snow & Marrs (1997)	Frond density (fronds/m^2) assessed over 36 months from 1992 on lowland heath (UK), latitude 53.35°.	1 application at 4.4kg a.i ha-1 in July using a knapsack sprayer.	2 data points. Factorial plot experiment concerned with heathland restoration. Litter was stripped exposing mineral subsoil for colonisation. Re-invading bracken was treated with asulam in three replicates (as part of a factorial experiment) and compared to totally untreated bracken. The baseline difference between treatment and control after litter stripping but prior to asulam application will therefore have a big impact on the result and limits its applicability with respect to the effectiveness of	Aggregate mean difference of -16.7 (control = 25.3)

			asulam on marginal land. The two asulam treatments (i.e. asulam after litter removal, asulam after litter removal and ploughing) are compared to the same control. Variance measures are not extractable for treatment and control.	
Marrs *et al* (1993)	Frond density (fronds/m^2) assessed over 144 months from 1978 on lowland grass heath (UK), latitude 52.30°.	1-2 applications at 4.4kg a.i ha-1 in August using a motorised backpack mistblower.	2 data points. Complex factorial experiment looking at the impact of different treatments (including asulam), heathland restoration and number of herbicide applications in two replicate blocks (n=2). The impact of asulam applied once and twice was extracted and is pseudoreplicated (n=4 rather than 2). Both treatments are compared to the same mean. Variance measures are not extractable for treatment and control.	Aggregate mean difference of -10.55 (control = 27.9)
Hamilton (1990)	Frond density (fronds/m^2) assessed over 34 months from 1986 in unspecified Australian habitat, latitude -37.7°.	1 application at 2.44kg a.i ha-1 in April using a carpet wiper.	2 data points. Unreplicated study with no validated baseline comparison and no consideration of any potential confounding effects. Its primary focus was the effectiveness of metsulfuron methyl rather than asulam which was studied in only one trial.	Aggregate mean difference of -2.77 (control = 15)
Oswald *et al* (1986)	Frond density (fronds/m^2) assessed over 22 months from 1982 on grassland (UK), latitude 51.13°.	1 application at 4.48kg a.i ha-1 in September using an Oxford Precision sprayer.	1 data point. Randomised replicated experiment, however, sample sizes are very small (n=3) and there is no reporting of variance.	Mean difference of -9.72 (control = 38)
Lowday (1985)	Frond density (fronds/m^2) assessed over 36 months, from 1981 on lowland heath (UK), latitude 52.30°.	1 application at 3.63kg a.i ha-1 in August using a weed wiper or rope wick applicator.	2 data points. Randomised block experiment with four replicates comparing asulam application once with a rope wick to two passes with a weed wiper and an untreated control A validated baseline is presented but the treatments are compared to the same control. Variance measures are not extractable for treatment and control.	Aggregate mean difference of -6.95 (control = 8)
Holroyd & Thornton (1978)	Frond density (log (100*x* +1) frond number per 10m^2) assessed over 27 – 37 months from 1970-1971 on grassland (UK), latitude 51.44°.	1 application at 2.2, 4.5 or 9kg a.i ha-1 in March, May, July, September or October using an Oxford Precision sprayer.	15 data points. Randomised controlled trials at three sites investigating the impact of different herbicides applied at different concentrations and times, with and without an adjunct, on bracken frond density. Replication is low (n=3) with no established baseline. Controls between months are independent but the different doses are compared to the same control. No variance data is presented. Two additional sites contain relevant data but lack measurements for control sites and cannot therefore be utilised.	Aggregate mean difference of -0.47 (control = 5.28)

Ecological characteristics provide details of each article's abundance measure, length of experiment (months), year experiment began, habitat type and latitude. Methodological characteristics provide details of number of herbicide applications, herbicide concentration (kg a.i ha-1), month of application and method of application. Study quality provides summary information regarding the number of data points provided by the article and experimental design. The outcome is expressed as the aggregate mean difference for the article with the control value presented for comparison.

Outcome of the review

Qualitative synthesis

The impact of studies examining the effectiveness of cutting (compared to no cutting) are summarised in Table 2.

Table 2. Methodological characteristics and outcomes of cutting *vs.* no cutting

Study	Characteristics	Outcome
Conway and Stephens (1954)	Complete defoliation by hand-cutting from plots measuring 10 ft x 10ft at intervals of 4 weeks through the growing seasons of 1950 – 1952. The cuts were made a) once, early in the growing season, b) twice, at the end of May and the end of June c) three times, at the end of May, the end of June, and the end of July. Assessment took place in September.	Slight increase in the total number of fronds. Increase in the number of rhizome tips carrying a frond bud. After 3 years of cutting the number of dead rhizomes increased, and expanded fronds was much smaller. Treatment c gave the best results, and b better than a.
Gordon (1916)	Six plots of 1/20 acre in size. Plots 1 and 2 were used as controls. Plot 3 was cut once, Plot 4 was cut twice, Plot 5 was cut 3 times, and Plot 6 whenever there was bracken appearing.	After one growing season plots 1 and 2 had dense crop of bracken. Plot 3 and 5 had a thin frond after treatment. Plot 4 had a dense crop of bracken. Plot 6 was bare of bracken.
Lowday *et al* (1983)	A randomised block experimental design was used with 4 blocks each containing 6 x 5m plots. The bracken was cut by mechanised scythe at intervals of two weeks from 6 June 1980. The cut fronds were not removed from the plot except for those in the sampling area (2 x 1m). Assessments were made fortnightly until September 1980, and then a final assessment in June 1981.	After cutting bracken regenerated, but amount depended on the time of cut; regrowth on plots cut after 18th July was progressively less vigorous.
Digby (1993)	A 4 x 4 latin square design was set up with experimental plots of size 1 x 1m. The treatments were a: Uncut control, b: cut in late June, C: cut in late July, d: Cut in late June and late July.	Frond numbers resulting from an early cut were greater than uncut plots. No such response was apparent when there was two cuts, and little stimulation in the later single July cut.

A further six studies comparing the effectiveness of cutting with asulam application are summarised in Table 3.

Table 3. Methodological characteristics and outcomes of cutting vs. asulam application

Study	Methodological characteristics	Outcome
Paterson *et al* (1997)	Six sites were selected across Britain to give a wide geographical spread. Each block contained 8 x 8m plots and was assigned the management regime 1) untreated control, 2) cut once yearly, 3) cut twice yearly (June and July), 4) asulam late July, 5) one cut, single application of asulam, 6) single application of asulam, one cut. Final assessment occurred three years after treatments.	Year 1: The total number of fronds produced within plots cut twice was significantly greater than other treatments. Year 2: Single cut increase frond density, Cutting twice reduced biomass. Year 3: Both cutting regimes reduced density – cutting once was less effective than cutting twice.
Marrs *et al* (1998)	An experiment was set up looking a range of bracken control treatments over an 18 year period. The 6 treatments were 1) untreated control, 2) cut once yearly in July, 3) cut twice yearly in June and July, 4) One application of asulam in August 1978, 5) Two applications of asulam, one in august 1978, the second in august 1979, 6) Asulam applied in August 1978, and then yearly cuts. This regime was maintained for 18 years (with further applications of asulam being made in 1984 and 1990.	After six years, the cut twice yearly, and the asulam plus cutting once yearly gave the best results. After 18 years all treatments had reduced bracken, the poorest result came from asulam applied on a six year cycle, and the best cutting twice yearly.
Snow and Marrs (1997)	Three bracken control treatments were applied, 1) bracken fronds cut once yearly in late July, 2) bracken fronds cut twice yearly in June and July, 3) application of asulam.	Application of asulam reduced frond density to a greater extent than either of the cutting treatments.
Lowday (1987)	A randomised block design on a uniform dense stand of bracken. Four replicates were used, each containing size 10 x 7 m plots (sampling are of 6 x 3m). The treatments were untreated, cut once/yr in late July, cut twice in mid June and late July, asulam treatment and then cutting once per year, and asulam twice (once in June, once in July).	All treatments significantly reduced the density of the bracken. The plots that were cut twice/year gave the greatest control of all interventions including asulam application; the plots cut once per year gave the lowest level of control.
Marrs et al (1993)	The treatments were untreated, cut once/yr in late July, cut twice in mid June and late July, and the remaining were asulam treatments. All treatments were applied in factorial combination (4x2x2=16) in two replicate blocks to plots 10 x 7m. Results were recorded after 10 years.	Cutting once yearly, and applying asulam, reduced the frond compared with the untreated control but cutting twice yearly for ten years gave the greatest amount of control.

Four out of the five studies comparing asulam with cutting found cutting twice a year to be more successful than asulam application. However, variation in the number of asulam applications and timescales of the studies hinder interpretation of these results. The experiments were carried out primarily on moorland or lowland heath at various sites across Britain, but sample sizes are too small to draw robust conclusions regarding the relative success of the treatments in different habitats at different latitudes. There is some evidence that mixed methods can also be more effective than asulam application alone (Marrs *et al.* 1998, Lowday 1987) although the number of studies is limited.

Other management interventions employed to control bracken include chemical alternatives to asulam. However, only asulam is licensed for aerial spraying (Bayer CropScience 2005) and no other chemicals have been adopted with the exception of glyphosate, which is only used where bracken is one of a number of weeds to control (Pakeman *et al.* 2000). Experiments on the effectiveness of herbicides other than asulam have been catalogued (Appendix 2) but sample sizes are too small to generate robust conclusions regarding the efficacy of any one herbicide. Experimental evidence regarding alternative interventions, namely mycoherbicides, insect biocontrol options, crushing using rollers, stock treading and burning was very scarce and therefore remains uncollated.

Experience of these management types, particularly crushing using rollers, stock treading and burning, is probably extensive, given their widespread use. Some unpublished experimental work and monitoring is ongoing; e.g. two sites in Sherwood Forest, (UK) have involved control using bracken rollers and monitoring has been undertaken for two years post-treatment (Denny *pers comm.*). The collation of such information would represent a considerable undertaking for a single researcher. However, the information is valuable, especially in the absence of any published information, and could be accessed via a centralised portal such as conservationevidence.com as advocated by Sutherland (Marris 2005). A robust trial examining the impact of bruising is also in progress (started in 2004) (Marrs *pers comm.*).

Meta-analysis of asulam studies

Data combined across studies using DerSimonian and Laird SMD random effects meta-analysis with effect size estimator Cohen's D resulted in a significant negative pooled effect size (d = -0.866, 95% CI = -1.336 to -0.395, P < 0.0001). There was significant heterogeneity (Q = 32.028, P < 0.006) and bias (Egger test = -6.17, P < 0.0001). Sensitivity analyses verified that the pooled effect size remained negative and significant with effect size estimators Hedges' adjusted *g* (includes a correction factor for small sample bias) and Glass's ? (uses control group standard deviation as a scaling factor thus a preferred option when the intervention alters variability).

The inclusion of multiple non-independent points from same study results in potential bias and distortion of weighting, thus the greatest possible independent effects (assuming conservative effectiveness of control) were combined as were the smallest (assuming maximum effectiveness of control). The conservative analysis resulted in a significant negative pooled effect size (Figure 1) (d = -0.513, 95% CI = -0.969 to -0.057, P < 0.027). Heterogeneity was not significant (Q = 7.39, P < 0.495) but bias was (Egger test = -7.048, P < 0.0001).

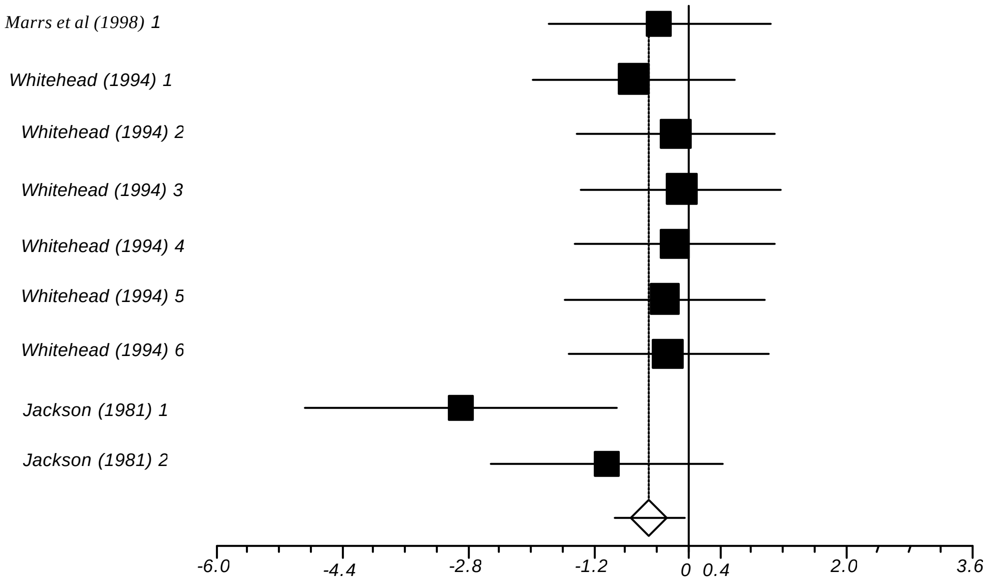

Figure 1. Forrest plot of individual effect sizes from nine conservative independent data points pooled using Standardised Mean Difference Random Effects Meta-analysis.

The maximum effectiveness analysis also resulted in a significant negative pooled effect size (Figure 2) (d = -0.685, 95% CI = -1.222 to -0.149, P < 0.012)). Again, heterogeneity was not significant (Q = 9.984, P < 0.266) but bias was (Egger test = -7.049, P < 0.0001).

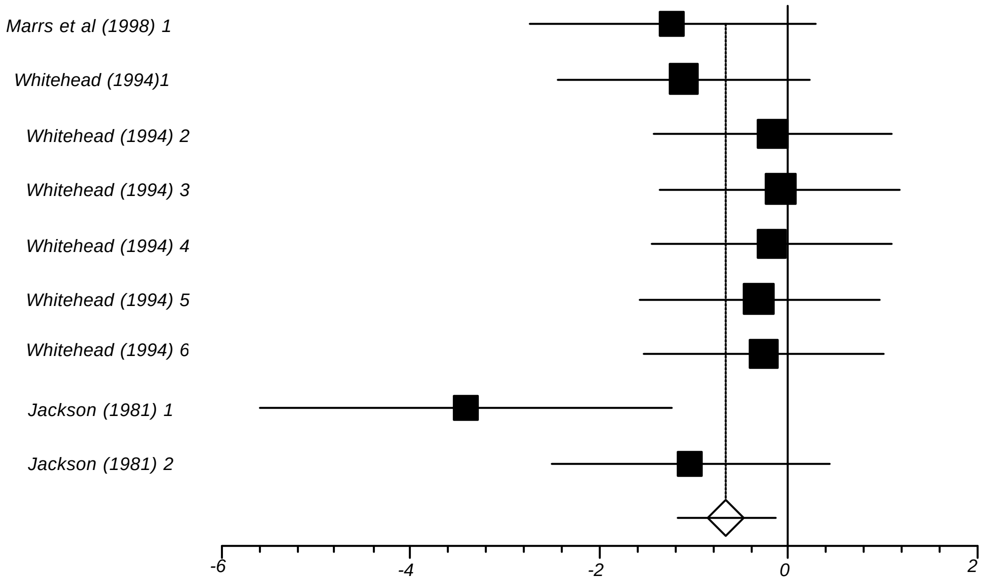

Figure 2. Forrest plot of individual effect sizes from nine maximum effectiveness independent data points pooled using Standardised Mean Difference Random Effects Meta-analysis.

Non-independent data were combined with imputed data where variance was missing, and again, the pooled effect size was negative and significant (d = -0.439, 95% CI = -0.699 to -0.179, P < 0.001). In this instance, neither heterogeneity nor bias were significant (Q = 43.319, P < 0.543, Egger test = -0.719, P < 0.323).

Exploration of reasons for heterogeneity
Univariate meta-regression was used to determine if habitat type, location, abundance measure, land management, length of experiment, number of herbicide applications, concentration of herbicide, time of application, method of application or year of application had any impact on the effectiveness of asulam. The number of herbicide applications and method of application had a significant impact on the effectiveness of asulam but the remaining variables did not (Table 4). This significance was not retained when all variables were considered concurrently in multivariate meta-regression.

Table 4. Univariate meta-regression coefficients and significance

Explanatory variable	Coefficient	Standard error	Z	P	Lower CI	Upper CI
Habitat type	-0.139	0.076	-1.83	0.067	-0.289	0.009
Location (latitude)	-0.002	0.007	-0.28	0.782	-0.017	0.013
Abundance measure	-0.094	0.283	-0.33	0.740	-0.650	0.462
Length of experiment	-0.003	0.002	-1.48	0.138	-0.008	0.001
Number of herbicide applications	-0.406	0.195	-2.08	**0.038**	-0.789	-0.022
Concentration of herbicide	0.071	0.053	1.35	0.177	-0.032	0.176
Month of application	0.008	0.081	0.11	0.913	-0.149	0.167
Method of application	0.175	0.067	2.59	**0.010**	0.042	0.308
Year of application	-0.006	0.014	-0.46	0.643	-0.036	0.022

The effectiveness of asulam was significantly increased when the number of applications increased. However, there are only four data points with more than three applications (Table 5). The use of a boom sprayer or motorised backpack mistblower appears more effective than other application methods. Hand spraying is less effective than the former techniques but appears more effective than the use of a knapsack sprayer, carpet wiper, oxford precision sprayer, rope wick applicator or weedwiper (Table 6). However, given the number of variables (n=9 for measured explanatory variables) and the sample size (46 non-independent points), these results must be interpreted with caution.

Table 5. The impact of number of asulam applications on effect size

Number of applications	**Mean Effect size (unweighted)**	**Standard Deviation**	**N (data points)**
1	-0.357	0.834	41
2	-0.070	0	1
3	-3.338	3.722	2
4	-3.260	4.012	2

Table 6. The impact of method of asulam application on effect size

Method of application	Mean Effect Size (unweighted)	Standard Deviation	N (data points)
Motorised backpack mistblower	-2.212	2.746	6
Hand sprayed	-0.527	0.448	8
Boom sprayer	-2.412	1.426	4
Knapsack sprayer	-0.080	0.022	8
Carpet wiper	-0.010	0.024	2
Oxford precision sprayer	-0.004	0.010	6
Rope wick applicator	-0.024	0	1
Weedwiper	-0.026	0	1

Discussion

Sample sizes were insufficient for quantitative analysis of bracken control interventions other than asulam application. The impact of cutting and herbicides other than asulam were therefore explored qualitatively.

Cutting

All studies that looked at the effectiveness of cutting compared to uncut controls show that cutting reduces frond abundance, and that multiple within growing season cuts are more effective than single cuts. However, the number of studies is limited (four studies compare cutting with no cutting with a further ten manuscripts comparing cutting with asulam application-see below). The potential for bias is large if these results are considered generic, given the small sample size and potentially large numbers of confounding variables.

Direct head to head comparisons of cutting and asulam application suggest that the former can be just as effective as the latter, provided that the fronds are cut once mid-June and again in late-July; however, this cutting regime needs to be repeated every year. Marrs *et al.* (1998) carried out a study for 18 years and obtained good control with cutting twice yearly. There are no longer term studies demonstrating complete eradication of the bracken by cutting. Small sample sizes prevent the generation of robust conclusions regarding the potential modifying effects of variables such as habitat or timing of cutting.

Current management recommendations are consistent with this literature and suggest that cuts should be made in June or July (SUP 2001, Marrs *et al.* 2005) with a dual cut necessary in the first year and annual yearly cuts for subsequent years (SUP 2001). Further synthesis of data comparing cutting and asulam application is ongoing (Cox *pers comm.*).

Herbicides excluding asulam

Robust conclusions cannot be drawn regarding the effectiveness of herbicides other than asulam because of small sample sizes and poor methodology. In general herbicides do reduce frond abundance, at least initially; however, recovery is inevitable if continuous spraying is not implemented. All the studies are short term thus the timescale for eradication of bracken is unknown. Glyphosate and metsulfuron-methyl are both reported to be more effective than asulam, although they are non-specific and not licensed for aerial spraying. The value in continuing experimentation with alternative herbicides is questionable because of the problems that arise due to their non-specificity.

Asulam application
Our analyses suggest that asulam application reduces the abundance of bracken. However, there is statistically significant bias when independent data (with variance measures) are analysed. This bias is not apparent when sample size is increased by utilising data with no variance measures and relaxing the requirement of independence. It is therefore possible that the bias associated with the smaller data sets arises because the small numbers of independent studies are in some way atypical. The bias could relate to systematic differences in the population characteristics at baseline (selection bias), differences in biotic and/or abiotic factors apart from the treatment during evaluation (performance bias), or biased assessment of outcomes (detection bias). It is clear from the study quality assessments (Table 1, Appendix 1) that there is considerable potential for selection and performance bias but sample sizes are too small for any quantitative assessment of their relative impacts. It is probable that variation in past treatment is a major source of bias, albeit unquantified, as it is extremely unlikely that all the bracken stands had similar histories prior to experimentation.

The data synthesised in the meta-analyses is largely derived from factorial experiments and randomised controlled trials. These experimental designs represent the "gold standard" of evidence (Stevens and Milne 1997), as they minimise the biases discussed above, but in ecology they can be misleading as they may be overly reductionist (Pullin *et al.* submitted). Concern has been expressed that bracken control experimentation does not replicate commercial treatment to clear bracken adequately (Robinson *pers. comm.*). In particular, the small scale of the plots and buffer strips between treatments are generally too small to avoid encroachment effects from adjacent bracken treatments, as established bracken rhizomes can remain active some five metres away from the edge of a stand. Small samples sizes and lack of rigorous monitoring in commercial situations preclude any quantitative analysis of the potential variation between experimental and "real world" situations in this instance.

Interpretation of the pooled effect size is complex because of the different abundance measures (frond biomass, frond density, number of active buds on rhizome) combined by expressing the difference between means relative to the variance. Most data in the analysis are frond data (as this is measured in most studies), but rhizome data are a far better indicator of bracken 'condition' than frond abundance (Pakeman *pers. comm.*). As well as increased persistence relative to fronds, rhizomes respond differentially to treatment with asulam, as frond origin may be from a long shoot rather than a short one (Marrs *pers comm.*). Reliance on frond data is likely to overestimate the impact of bracken control in relation to rhizome data especially in the short-term, as bracken fronds dieback (and subsequently regenerate) faster than rhizomes, which are far more persistent (Marrs *et al.* 1998). Furthermore, frond biomass and density do not follow a 1:1 relationship, as frond density can remain high when both height and biomass are reduced, particularly when stands are controlled by cutting and to a lesser extent by herbicide application (Marrs *et al.* 1998). Again, this is likely to increase the value of the pooled estimate, as there are more density measures than biomass measures in the analysis. Sample sizes are insufficient to allow quantitative exploration of all these relationships, although rhizome data was compared to frond data in the meta-regression (see below).

It is not surprising that asulam application reduces the abundance of bracken, especially given the short timescales of the majority of the included studies (Table 1). Asulam is marketed by Bayer CropScience (under the trade name Asulox®) specifically for the control of bracken and docks (Bayer CropScience 2005), and all the primary studies included in this review show that its application reduces bracken abundance (Table 1). However, reasons for variation in the impact of asulam are crucially important from a management perspective.

Exploration of reasons for heterogeneity

i) Number of asulam applications
Univariate meta-regression demonstrates that the number of asulam applications has a statistically significant ($P < 0.038$) impact on the effect of asulam on bracken abundance. Furthermore, the meta-regression coefficient is large (Table 2), indicating that multiple applications of asulam are necessary for effective control. Bayer CropScience acknowledge that 100% control is rarely achieved and state that surviving bracken fronds should be retreated when they are fully expanded either in the year following application, or more likely the second year after application (Bayer CropScience 2005). Likewise, Le Duc *et al.* (2000) found that bracken regeneration towards dominance was occurring at 75% of sites subject to a single application of herbicide. There is therefore a general consensus that continuing follow up treatment is required (Pakeman *et al.* 2000, 2002). Bracken regeneration rates vary without follow up but increase substantially after five years (Pakeman *et al.* 2002;, Bayer CropScience 2005), largely negating the effect of the initial treatment; thus, repeat spraying on a five to seven year cycle does not control bracken effectively over long timescales (Pakeman *et al.* 2005). The meta-regression results suggest that multiple follow up is required if bracken control is to be effective with three or four applications, approximately ten times more effective than one or two (Table 3). However, this result is based on limited data. Only four data points have more than three follow up treatments. There are also problems with confounding effects as these points represent the longest follow up (Table 1).

Current management recommendations for bracken control using asulam reflect the need for follow up and the differing objectives of control and eradication but fail to provide precise guidance on the number of follow ups and timescales (SUP 2001, Pakeman *et al.* 2005). In particular, the objectives for releasing work, where bracken is an integral component of the vegetation, with conservation value, are never properly defined. For example, very few, if any, authoritative guidelines for management of Fritillary butterflies exist (Robinson *pers comm.*). Obviously it is impossible to assess under what circumstances an intervention is applicable if the desired outcome is not precisely defined.

The longest studies included in the analysis received three or four applications of asulam over 18 years reducing frond densities to approximately 50% of control plot density (based on unweighted aggregate means) (Table 1). Total eradication of bracken using asulam has not been demonstrated experimentally although virtual eradication has been achieved by continued follow up annually over 8-9 years on *Calluna* moorland on Spaunton Moor (North York Moors, UK). Evidence of the success of this clearance endeavour is provided by before and after photography spanning 20 years and by the widespread occurrence of fossil rhizomes on areas now dominated by *Calluna vulgaris*. However, formal monitoring data and exact treatment records do not exist. Formal experimentation is underway to test whether a single spray and follow-up spraying of all survivors without remit can eradicate bracken (Marrs *pers comm.*).

ii) method of asulam application

The method of application had a statistically significant ($P < 0.010$) impact on the effect of asulam on bracken abundance although the meta-regression coefficient is not large (Table 2) suggesting that the impact of method of application is smaller than the impact of number of applications.

The use of a boom sprayer or motorised backpack mistblower appears more effective than other application methods (Table 4). However, the study utilising a boom sprayer may have overestimated the effect size because the baseline was not comparable prior to herbicide application (Table 1). Furthermore, the results from this study have limited relevance to marginal land as it was undertaken in a cultivated system. Data regarding mistblowers were derived from two studies, both involving multiple applications of herbicide (Table 1) thus the large effect size could reflect this rather than method of application. Hand spraying is less effective than the former techniques but appears more effective than the use of a knapsack sprayer, carpet wiper, oxford precision sprayer, rope wick applicator or weedwiper (Table 4). However, the studies involving hand spraying were short-term resulting in a potential overestimate of effectiveness. Additionally, the outcome measure relates to the number of active buds on rhizome segments and some of these data are derived from *ex situ* experimentation where disturbance could distort results (Table 4). An additional problem is that the different methods are utilised in different circumstances. For example, weed wiping is not used to control dense bracken but as a follow-up treatment or treatment to sparse bracken (Marrs *pers comm.*). The baselines, from which control was initiated is therefore likely to further confound the relationships described above.

Current management recommendations for method of asulam application are based on cost and practical constraints rather than effectiveness (SUP 2001, Pakeman *et al.* 2005) e.g. Knapsack spraying is useful for small areas but tiring due to weight of water carried and is therefore less appropriate than a tractor mounted machine for large areas, assuming the tractor can safely negotiate the terrain (Pakeman *et al.* 2005). However, caution has been expressed about the use of Low volume drift sprayers with Micron Ulva's which result in less reliable control than spray methods unless there is a steady wind of 5-20km per hour (Bayer CropScience 2005, Pakeman *et al*. 2005). Our results suggest that application methods do impact on effectiveness, although the potential for bias, number of confounding factors and lack of studies on common practices such as aerial spraying prevent the generation of robust conclusions about the relative effectiveness of one technique over another. The only large-scale long-term survey on the success of aerial spraying concurs with the current work concluding that good practice where bracken is controlled through the use of herbicides is initiated through a blanket spraying (whether from the air or from a ground-based vehicle), but regrowth in subsequent years should always be resprayed and never given a chance to initiate regeneration (Pakeman *et al*. in press). Thus, number of applications is more critical than method of application.

iii) other variables

No measured variables other than number and method of application had a statistically significant impact on the effect of asulam on bracken abundance. Habitat type might be expected to modify the effectiveness of bracken control strategies as different vegetation types have different productivities and competitive interactions. However, there was no evidence of habitat acting as an effect modifier in the current work.

The rate and direction of post-herbicide-application vegetation succession has been highly correlated with longitude, latitude and distance from the sea (Le Duc *et al.* 2000); with Western Britain and coastal sites showing more rapid increases in vegetation cover, possibly as a result of larger species pools or more rapid breakdown of litter in the wetter climate (Pakeman *et al.* 2001). It is therefore notable that latitude did not have a significant impact on the effect of asulam on bracken abundance. Land management also plays a critical role in directing succession but information on management practices was either insufficiently detailed for inclusion in meta-regression or was unreported.

Bracken does not respond well to drought (Pakeman *et al.* 2000), therefore soil moisture could potentially impact the efficacy of bracken control. There was insufficient reporting of soil moisture in primary studies for this variable to be included in meta-regression.

The abundance measures synthesised across studies mostly related to frond abundance but the number of active buds on rhizome segments was also used as a measure of the success of asulam application (Table 1, appendix 1). This did not have a significant effect on the results despite the complex relationships between above and below ground biomass, active and dormant buds and asulam uptake (Whitehead 1993, Pakeman and Marrs 1994b).

The length of time monitoring or running experiments would be expected to have a considerable impact on the results because bracken recovers very quickly from initial treatment (Pakeman *et al.* 2002, Bayer CropScience 2005, Pakeman *et al.* 2005). The fact that experimental length was not significant probably reflects the fact that the longer timescales involved multiple treatments.

Herbicide concentration would also be expected to have a large impact on the results. Bayer CropScience recommend application at 4.4kg a.i ha-1 (Bayer CropScience 2005). The data set included both sub-lethal concentrations and above-lethal concentrations but no significant differences were apparent, possibly as a result of confounding or lack of power.

Bayer CropScience recommend application of asulam at or just before full frond extension (minimum 3 pairs of pinnae) and before senescence (Bayer CropScience 2005). Full frond expansion prior to any die back of tips occurs between mid July to late September depending on altitude and locality (Pakeman *et al.* 2005). Some data points were outside this range and might be expected to exhibit sub-optimal effectiveness; however there was no significant impact of timing. As with other variables, this could reflect confounding or lack of power.

Review limitations

This review is concerned solely with the impact of control methodologies on bracken abundance. Standard inferential meta-analysis of interventions other than asulam application was not possible given the small sample sizes. However, correlative studies or Bayesian analyses incorporating lower levels of evidence could provide alternative means of synthesising this information. Quantitative analysis was restricted not only to asulam but also to bracken abundance. In particular, there was no consideration of the impact of interventions on non-target species or subsequent vegetation succession. There is a large body of literature on vegetation succession following bracken control as directing vegetation change is usually the underlying management objective (Le Duc *et al.* 2000, Pakeman *et al.* 2005, Pakeman, R.J. (1994a, 2000, 2001, 2002). Multivariate synthesis and meta-analysis of these data would require large sample sizes if robust conclusions were to be drawn without problems of confounding. Even in relatively simple models, with the outcome restricted to changes in bracken abundance, confounding, bias and lack of power due to small sample sizes hinder the interpretation of results. These problems are likely to be exacerbated in a complex multivariate system.

Further problems, associated with small sample sizes and confounding, centred on lack of information. The lack of statistical significance for many potential effect modifiers is arguably as likely to reflect lack of data as lack of a relationship. Sample sizes were small and only a few habitats and latitudes were included in the analysis. Soil moisture and land management practices were insufficiently reported for inclusion in meta-regression. There was no experimental work involving aerial spraying or application with micron Ulvas in the data sets. There were insufficient numbers of studies presenting independent rhizome and frond data. More long term monitoring is required to fully ascertain the impact of time on effectiveness of control. Likewise, further studies looking at herbicide concentration and time of application are required to ascertain that management recommendations are generic rather than site specific. Some of the unreported data may have been available if greater effort had been expended contacting authors. However, asking researchers for unpublished information is often unsuccessful (Hetherington 1989, Horton 1997), and the small sample sizes and multiple variables would have continued to hinder interpretation.

The scope of this review was global but the retrieved data were predominantly UK based. This may reflect data availability but the applicability of the results to many areas where bracken is a problem remains unknown.

The review was based on comparison of treatment and control or before and after impact data. Ideally, synthesis would be undertaken using rates of change derived from randomised replicated studies or combining rates of change from monitoring. These data were largely unavailable (not presented in the research literature) and it was considered inappropriate to synthesise rates of change with different abundances where it was potentially available. However, if raw data were available, further synthesis would possible. Synthesis of large scale information from sources such as countryside survey, involving primary research, was outside the scope of this work but would also provide useful additional information.

At the time of writing some bracken control studies are ongoing, including continuation of work from studies included in this review and a commercial proving trial concerning asulam, now at the end of its third year at Spaunton Moor (Robinson *pers comm.*). Some monitoring of rolling impacts in Sherwood Forest has been initiated by English Nature, although additional funding is required to extend and continue with this valuable work. Subject experts have also identified relevant material that was not included in the analysis (Williams & Foley 1975, Williams 1977, Williams & Fraser 1979, Pakeman & Marrs 1994b). Further collaborative data synthesis comparing the impact of different interventions using raw data is also planned (Cox *pers comm.*). It may therefore become appropriate to update this review when more information is available.

Reviewers' conclusion

Implications for Management
Available evidence suggests that asulam application reduces the abundance of bracken although subsequent regeneration can be rapid. Multiple applications of asulam are more effective than single applications, slowing the speed of recovery. More high quality research and monitoring is required to ensure that current management recommendations are generic, rather than site specific, but there is no evidence that they require modification. However, much current control consists of a single application of asulam with no or limited follow up. This is ten times less effective than control with multiple follow up. It is therefore more effective to spray a fifth of a site five times over five years than the whole site once. The former results in decreased bracken abundance across a fifth of the site, whilst the latter may have no effect at all by the fifth year. Qualitative evidence suggests that cutting could be as effective as asulam application, particularly if two cuts are applied within the same growing season, but further work is required for corroboration.

Implications for further research.
Further research is required to fill a number of knowledge gaps regarding the impact of bracken control strategies. There is a lack of head to head comparisons regarding the effectiveness of different control strategies. In particular long term work comparing cutting and asulam application is required to build on the existing work. There is no robust experimental evidence regarding the impact of rolling on bracken abundance, although the technique is being applied at a small scale on inaccessible ground unsuitable for cutting machinery. Ongoing monitoring of rolling impacts and experimentation on bracken bruising should receive funding to ensure its continuity.

With respect to asulam application, further information is needed on the number of follow up treatments and aftercare required for specified levels of desired control. Complete eradication of bracken using asulam has not yet been demonstrated experimentally although Spaunton Moor, UK provides evidence that virtual eradication is possible. Further work is also required regarding the efficacy of different application techniques as this work suggests that their effectiveness is variable. The impact of many effect modifiers such as habitat, location and land management also require further investigation across multiple sites if generic bracken control strategies are to be validated. Further meta-analysis is ongoing but this should be augumented with the collection of additional data to increase samples sizes and minimise confounding effects.

Future experimental work should give careful consideration to abundance measures. Although, easily measured, frond density in not a good measure of bracken abundance as it fluctuates rapidly. Rhizome abundance is considered the optimal measure, preferably measured alongside frond biomass.

Further primary studies are an essential component of the required research but further synthesis of large scale information e.g. correlating countryside survey vegetation change data with areas where bracken control has been funded through

agri-environment schemes; and monitoring the effectiveness of bracken control where aerial spraying has occurred, could also be valuable tools.

However, some researchers believe that further research on control would necessarily detract from research on other topics; namely the steps needed to regenerate appropriate vegetation after control and also what is causing bracken to spread in the first place. These topics are beyond the scope of the existing review but important questions worthy of further attention.

Acknowledgements

We would like to thank all the authors and organisations who responded to our enquiries. Special thanks to Rob Marrs for guidance, comments and access to the complete applied vegetation science bracken database, Roderick Robinson of Bayer CropScience for guidance, comments and a site visit, George Wynn Darley of the Moorland Association for a tour of his estate, Robin Pakeman for information and valuable comments, Matthew Denny for information regarding rolling members of the International Bracken Group who patiently answered our queries. We have found the "bracken community" to be open, friendly and helpful, which greatly facilitated the production of this review.

Potential Conflicts of Interest and Sources of Support

None declared: This review was funded by English Nature and The Royal Society for Protection of Birds.

References

Bailey, K. (1987) Inter-study differences: how should they influence the interpretation and analysis of results? *Statistical medicine* **6**, 351-8.

Barr, C.J. *et al* (1993) *Countryside Survey 1990: Main Report.-Countryside 1990 Series: Volume 2.* Department of the Environment, London.

Bayer CropScience (2005) http://docushare.bayercropscience.co.uk/Asulox.pdf

Cooper, H. & Hedges, L.V. (1994) (eds.) *The Handbook of Research Synthesis*. Russell Sage Foundation, New York.

Chadwick, L. (2003) The Farm Management Handbook 2003/04. Scottish Agricultural College, Edinburgh.

Deeks, J.J., Altman, D.G. & Bradburn, M.J. (2001) Statistical methods for examining heterogeneity and combining results from several studies in meta-analysis. In, *Systematic Reviews in Health Care: Meta-analysis in Context*. M. Egger, G.D. Smith and D.G. Altman. (Eds.) p 285-312. British Medical Journal Publishing Group, London.

Department for Environment, Food and Rural Affairs (2003a) *The Countryside Stewardship Scheme 2004. Information and how to apply.* Department for Environment, Food and Rural Affairs, London.

Department for Environment, Food and Rural Affairs (2003b) *The Countryside Stewardship Scheme 2004. Payment Summary Sheet.* Department for Environment, Food and Rural Affairs, London.

DerSimonian, R. & Laird, N. (1986) Meta-analysis in clinical trials. *Controlled. Clinical Trials* **7**, 177-188.

Egger M, Davey-Smith G, Schneider M & Minder C. (1997) Bias in meta-analysis detected by a simple graphical test. *British Medical Journal* **315**, 629-34.

Haines-Young, R.H., *et al.* (2000) *Accounting for Nature: Assessing Habitats in the UK Countryside*. Department of the Environment, Transport and the Regions, London.

Hetherington, J., Dickersin, K., Chalmers, I., & Meinert, C.L. (1989) Retrospective and prospective identification of unpublished controlled trials: lessons from a survey of obstetricians and pediatricians. *Pediatrics* **84**, 374-80.

Horton R. (1997) Medical editors trial amnesty. *Lancet* **350**, 756.

Khan, K.S., ter Riet, G., Glanville, J., Sowden, A.J. & Kleijnen, J. (eds.) 2001. Undertaking systematic reviews of research on effectiveness. *NHS Centre for Reviews and Dissemination, report number* **4**, 2nd edition, University of York.

Lawton, J.H. & Varvarigos, P. (1989) *Socio-economic aspects of bracken control.* University of York, York.

Le Duc, M.G., Pakeman, R.J. & Marrs, R.H. (2000) Vegetation changes after treatment for bracken (*Pteridium aquilinum*) control, by herbicide, on upland and marginal areas of Great Britain. *Journal of Environmental management* **58**, 147-160.

Marris, E. (2005) Taking the quackery out of conservation: news feature. *Nature* **437**: 616.

Morton, S., *et al*. (2001). Meta-analysis of messy data: problems and solutions from a meta-regression analysis of spinal manipulation for low back pain. *Cochrane* **1**: op024.

Pakeman, R.J. & Marrs, R.H. (1994a) *Bracken control and vegetation restoration: Literature Review*. Report to Ministry of Agriculture, Fisheries and Food. June 1994.

Pakeman, R.J. & Marrs, R.H. (1994b) The effects of control on the biomass, carbohydrate content and bud reserves of bracken (*Pteridium aquilinum* (L.) Kuhn), and an evaluation of a bracken growth model. *Annals of Applied Biology* **124**, 479-493.

Pakeman, R.J. & Marrs, R.H. (2001) The development of effective strategies for controlling bracken and restoring vegetation. In S. Rees, R. Charles & S. Wightman (Eds) *Moorland Research Review 1990-1995.* pp. 48-53. North York Moors National Park Authority, Helmsley.

Pakeman, R.J. & Sangster, H. (2000). Bracken control and vegetation restoration. *Bracken Fern: Toxicity, Biology and Control*. J.A. Taylor & R.T. Smith (Eds). International Bracken Group Special Publication Number **4**. pp. 195-196.

Pakeman, R.J., Le Duc, M.G. & Marrs, R.H. (2001) Integrating bracken control and vegetation restoration. *Moorland Research Review 1995-2000.* North York Moors National Park Authority, Helmsley. pp. 37-40.

Pakeman, R.J., Le Duc, M.G. & Marrs, R.H. (2002) A review of current bracken control and associated vegetation strategies in Great Britain. *Web Ecology* **3**, 6-11.

Pakeman, R.J., Le Duc, M.G. & Marrs, R.H. (2005) *Bracken control, vegetation restoration and land management.* Rural Development Service.

Pakeman, R.J., Marrs, R.H. & Le Duc, M.G. (2000) Bracken distribution and control methods: their implications for the sustainable management of marginal land in Great Britain. *Annals of Botany* **85** (Suppl. B), 37-46.

Pakeman, R.J., Marrs, R.H. & Le Duc, M.G. (2000) Bracken distribution in Great Britain: strategies for its control and the sustainable management of marginal land. In J.A. Taylor & R.T. Smith (Eds) *Bracken Fern: Toxicity, Biology and Control*. International Bracken Group Special Publication Number **4**. pp. 185.

Pakeman, R.J., Small, J.L., Le Duc, M.G., & Marrs, R.H. (in press) Recovery of moorland vegetation after aerial spraying of bracken (*Pteridium aquilinum* (L.) Kuhn) with asulam. *Restoration Ecology.*

Pullin, A., & Knight, T.M. (2001) Effectiveness in conservation practice: pointers from medicine and public health. *Conservation Biology* **15**, 50-54.

Pullin, A.S. & Knight, T.M. (2003) Support for decision making in conservation practice: an evidence-based approach. *Journal for Nature Conservation* **11**, 83-90.

Pullin, A., Knight, T.M., Stone, D., & Charman, K. (2004) Do conservation managers use scientific evidence to support their decision-making? *Biological Conservation* **119**, 245-252.

Scottish Executive (2003) *Rural Stewardship Scheme.* Scottish Executive, Edinburgh.

Sharp, S. (1998) Meta-analysis regression: statistics, biostatistics, and epidemiology. *Stata Technical Bulletin*.**42**, 16-22.

Southern Uplands Partnership (2001) *Bracken Control: A guide to best practice*. Southern Uplands Partnership, Galashiels.

Stevens, A. & Milne, R. (1997). The effectiveness revolution and public health. In: G. Scally (Ed.) *Progress in Public Health*, p197-225. Royal Society of Medicine Press, London.

Sutherland, W., Pullin, A.S., Dolman, P., & Knight, T.M. (2004) The need for evidence-based conservation. *Trends in Ecology and Evolution* **19**: 305-308.

Thompson, S.G. & Sharp, S.J. (1999). Explaining heterogeneity in meta-analysis: a comparison of methods. *Statistics in Medicine* **18** (20), 2693-2708.

Thompson, S.G. (1994) Why sources of heterogeneity in meta-analysis should be investigated. *British Medical Journal* **309**, 1351-1355.

Wardman, O.L. & Thomas, M.R. (2003) Aerial Applications, Great Britain 2002. *Pesticide Usage Survey Report* **186**. Central Science Laboratory, York.

Wardman, O.L. & Thomas, M.R. (1999) Aerial applications, Great Britain 1998. *Pesticide Usage Survey Report* **158**. MAFF, London.

Whitehead, S.J. (1993) *The morphology and physiology of moorland bracken (Pteridium aquilinum) and their implications for its control.* Thesis, University of York.

Williams, G.H. & Foley, A. (1975) Effect of herbicides on bracken rhizome survival. *Annals of Applied Biology* **75**, 109-111.

Williams, G. H. (1977). Qualitative effects of asulam and glyphosate on swards dominated by bracken (Pteridium aquilinum (L.) Kuhn). *Journal of the British Grassland Society* **32**, 149-155.

Williams, G. H. & Fraser, D. (1979). The effects of asulam, frond cutting and ground mineral phosphate on the yields of swards dominated by bracken (*Pteridium aquilinum* (L.) Kuhn). *Grass and Forage Science* **34**, 95-100.

Wolf, F. & Guevara, J. (2001). Imputation of missing data in systematic reviews: so what is the standard deviation? *Cochrane* **1**: pa007.

Appendices

Appendix One: Table of included studies.

Study	Hamilton, L. J. (1990). Evaluation of metsulfuron methyl for bracken control. *Bracken Biology and Management*. (eds) J. A. Thomson and R. T. Smith. Sydney, Australian Institute of Agricultural Science: 291-297	
Methods	Four trials comparing the effects of asulam and glyphosate to metsulfuron methyl with and without additives (Ulvapron, Li 700 and Pulse). Only one unreplicated site examined asulam use (with and without Ulvapron)	
Population	*Pteridium esculentum* in East Victoria, Australia on sandy loam soil.	
Intervention and Co interventions	No details of land management are provided	
Outcomes	Trial 1	Bracken density (frond/m^2)
	asulam with no additive	16.90
	asulam with Ulvapron	7.55
	Untreated control	15.00
Study design	For the purposes of asulam impact two treatment sites are compared to one non-independent control 34 months after asulam application	
Baseline Comparison	It is stated that average pre treatment frond density is 17.3 fronds/m^2. However it is not clear which treatment or which of four trials this figure refers to; or how it was derived.	
Intra treatment variation	The relevant trial (1) and control plot were assessed using four transects with 25 measurements per transect but no data is presented on variation within (pseudo)replicates.	
Measurement of intervention and Co-interventions	No interventions other than application of asulam are mentioned. Asulam dose is stated as 2.4 litres a.i./ha with no other information. It is assumed that this represents 2.4kg a.i ha^{-1}.	
Replication	There is no replication (n=1). Pseudoreplicated variance measures are not presented.	
Parameter of abundance	Above-ground bracken abundance measured in bracken fronds/m^2	
Size of experimental area	Trial 1 has plot sizes of 20m x 50m (big enough to prevent rhizome ingression from out with the plot).	
Notes	This is an unreplicated study with no validated baseline comparison and no consideration of any potential confounding effects. It's primary focus was the effectiveness of metsulfuron methyl rather than asulam which was studied in only one trial.	

Study	Oswald, A. K., Richardson, W.G., & West, T.M. (1986) The potential control of bracken by sulphonyl-urea herbicides. *Bracken: Ecology, land use and control technology*. (eds) R. T. Smith and J. A. Taylor. Carnforth, Lancs, Parthenon Publishing Group: 431-440.		
Methods	A randomised control trial looking at the effect of different herbicides including asulam on frond density.		
Population	U4 moorland sward with bracken. Rippon Tor, Devon, England. Bracken density was 21 fronds/m^2 prior to experiment.		
Intervention and Co interventions	The site had been grazed by sheep and wild ponies. Asulam was applied and the impact on frond density assessed after 22 months.		
Outcomes	Study	Frond density/m^2	Fresh weight of rhizomes (g/plot)
	Asulam application	26	180
	Control	38	264

Study design	A randomised control trial
Baseline Comparison	There is insufficient information to judge the validity of the baseline although randomised replicates should minimise bias
Intra treatment variation	There is no reporting of variance within treatments or (pseudo)replicates within plots.
Measurement of intervention and Co-interventions	Grazing has previously occurred on the site
Replication	There were 3 replicates
Parameter of abundance	Number of fronds/m^2 in 3- 1m^2 quadrats per replicate (fresh weight of rhizomes (g/plot) were recorded but are not used in subsequent analysis).
Size of experimental area	5m^2 x 2.5m^2
Notes	This is a randomised replicated experiment, however, sample sizes are very small (n=3) and there is no reporting of variance making it difficult to assess the robustness of the data.

Study	Whitehead, S.J. (1994) *The morphology and physiology of moorland bracken (Pteridium aquilinum (L.) Kuhn) and their implications for its control*. Thesis. University of York, York, UK
Methods	A large number of experiments and treatments are presented. An *ex situ* experiment investigates the response of active rhizome buds to three sub-lethal concentrations of asulam (using the same control). The same phenomenon is investigated in the field at five points across replicated *Calluna/Pteridium* interfaces (using independent controls but not independent points).
Population	The *ex situ* experiment used bracken rhizomes from a dense bracken stand on the North York Moors. The field experiment was undertaken across a *Calluna/Pteridium* interface with two points dominated by bracken and three dominated by *Calluna.*
Intervention and Co interventions	The intervention was application of sub-lethal doses of asulam. The North York Moors are managed largely by burning in the area of experimentation but specific site management details are not presented.

Outcomes (the number of active buds on the rhizome is the outcome for both experiments)

	Treatment			Control		
Treatment	Mean	N	SD	Mean	N	SD
0.16kg a.i ha-1	31	5	8.94	65	5	38.01
0.48kg a.i ha-1	43	5	13.42	65	5	38.01
0.8kg a.i ha-1	35	5	2.24	65	5	38.01
U20	25	4	60	44	6	125
U20	24	4	56	31	6	81
Calluna	13	4	32	25	6	73
Calluna	3	4	11	16	6	48
Calluna	0.5	4	2	4	6	15

Study design	The studies are both quasi-randomised control trials (neither state method of randomisation and the *ex situ* experiment has no independent control, whilst the field experiment has independent controls but used non-independent populations in the same transects)
Baseline Comparison	There is insufficient reporting of baselines (for either experiment) to assess the potential for bias although the use of replication and randomisation should have minimised the potential effects of variation particularly in the *ex situ* experiment (environmental factors controlled).

Intra treatment variation	Variance measures are reported for the outcome but there are no details of variation between replicates with respect to baseline conditions.
Measurement of intervention and Co-interventions	There is no detailed information on site management prior to treatment
Replication	Studies are replicated (see outcome for sample sizes)
Parameter of abundance	Counts of number of active buds in $0.5m^2$. subsampled from $1m^2$ quadrats.
Size of experimental area	The *ex situ* experiment utilised blocks $0.5m^2$.The field experiment was based on $1m^2$ quadrats in 5m long transects. (Rhizome ingression is a probable source of error in the field experiment, whilst severing rhizomes for the *ex situ* experiment limits the applicability of results to bracken control in the field although it controls for environmental variation, a point covered by the author)
Notes	Both experiments are replicated but both have problems of independence and the potential for rhizome ingression/disturbance is problematic as is the short timescale. There is potential error associated with data extraction as means and standard errors were read off graphs in the absence of tables. The parameter of abundance is difficult to compare with measures of frond abundance, biomass or density reported in other studies.

<table>
<tr><td>Study</td><td colspan="7">Jackson, L. P. (1981). Asulam for control of eastern bracken fern in Lowbush Blueberry Fields. Canadian Journal of Plant Science 61(2): 475-477.</td></tr>
<tr><td>Methods</td><td colspan="7">A randomised controlled trial in blueberry bush fields utilising two sites and two herbicide concentrations (The sites are independent but the concentration treatments are compared to the same mean)</td></tr>
<tr><td>Population</td><td colspan="7">Bracken in blueberry fields</td></tr>
<tr><td>Intervention and Co interventions</td><td colspan="7">Asulam applied at 1.12 and 2.24 Kg/ha a.i. cointervention is blueberry cultivation</td></tr>
<tr><td rowspan="6">Outcomes (the number of fronds per $100m^2$).</td><td></td><td colspan="3">Treatment</td><td colspan="3">Control</td></tr>
<tr><td>Treatment</td><td>Mean</td><td>n</td><td>SD</td><td>Mean</td><td>n</td><td>SD</td></tr>
<tr><td>Site 1, 1.12kg/ha</td><td>3.5</td><td>4</td><td>7.18</td><td>42</td><td>4</td><td>14.66</td></tr>
<tr><td>Site 1, 2.24kg/ha</td><td>1.25</td><td>4</td><td>0.82</td><td>42</td><td>4</td><td>14.66</td></tr>
<tr><td>Site 2, 1.12kg/ha</td><td>1.75</td><td>4</td><td>3.3</td><td>34.5</td><td>4</td><td>38.72</td></tr>
<tr><td>Site 2, 2.24kg/ha</td><td>1.5</td><td>4</td><td>4.44</td><td>34.5</td><td>4</td><td>38.72</td></tr>
<tr><td>Study design</td><td colspan="7">Both studies are randomised controlled trials</td></tr>
<tr><td>Baseline Comparison</td><td colspan="7">The authors report fully on the baseline. There is considerable variation in bracken density before treatment especially in site 2. Presumably, environmental factors are relatively uniform as the plots are in an arable system.</td></tr>
<tr><td>Intra treatment variation</td><td colspan="7">The authors provide standard errors for bracken density and they are considerable especially for site 2.</td></tr>
<tr><td>Measurement of intervention and Co-interventions</td><td colspan="7">Asulam application and blueberry production are recorded.</td></tr>
<tr><td>Replication</td><td colspan="7">N=4 (see outcomes0</td></tr>
<tr><td>Parameter of abundance</td><td colspan="7">Average number of fronds per $100m^2$.</td></tr>
<tr><td>Size of experimental area</td><td colspan="7">2x10m contiguous plots were used at each site, therefore ingression of rhizomes could be a source of error</td></tr>
</table>

Notes	A replicated randomised trial with good reporting of baseline which unfortunately was not comparable with respect to bracken abundance and had high variance prior to experimentation. The application of results from such a cultivated system to marginal land bracken control could also be questionable.

Study	Marrs, R.H., Johnson, S.W. & Le Duc, M.G. (1998) Control of bracken and the restoration of heathland 7. The response of rhizomes to 18 years of continued bracken control or six years of control followed by recovery. *Journal of Applied Ecology* **35**, 748-757.						
Methods	Complex factorial experiment looking at the impact of different controls (including asulam) and associated treatment in two replicate blocks (n=2). The impact of asulam applied three times and four times after eighteen years was extracted separately for each replicated block as it is presented in the manuscript although it appears that the control plot represents pooled data (mean and sd identical).						
Population	U20 on a Lowland *Calluna* heath.Cavenham heath, UK.						
Intervention and Co interventions	Asulam applications						
Outcomes (frond biomass g/m^2).		Treatment			Control		
		Mean	n	SD	Mean	n	SD
	S1, 3 times (18yrs)	93	4	60.4	404.2	4	57.8
	S1, 4 times (18yrs)	87.8	4	45.2	404.2	4	57.8
	S2, 3 times (18yrs)	247.8	4	145.4	404.2	4	57.8
	S2, 4 times (18yrs)	363.4	4	123.4	404.2	4	57.8
Study design	Well designed factorial experiments						
Baseline Comparison	No details of the baseline are reported in this manuscript but it is described in previous work. Factorial design minimises bias						
Intra treatment variation	See baseline comparison						
Measurement of intervention and Co-interventions	Application of asulam. Grazing by deer and rabbits						
Replication	The factorial plots are replicated twice. Within each plot n=4. However, differences between seeding and non-seeding were not significant so these can be pooled (n=8). Extracted data is based on n=4.						
Parameter of abundance	Frond biomass g/m^2 was extracted but rhizome data is also presented						
Size of experimental area	Experimental plots were 10mx7m with 1m buffer zones to account for rhizome ingression						
Notes	Well designed experiment. However, extracted data is pseudoreplicated because variance data is presented independently for the two true replicates (n=4 rather than 2). There are problems with independence within and between replicated blocks as the treatments are compared to the same mean which is identical for both replicates (pooled mean?). This work is one of very few longer term bracken control studies.						

Study	Snow, C. S. R. and R. H. Marrs (1997). Restoration of Calluna heathland on a bracken Pteridium- infested site in north west England. *Biological Conservation* **81**(1-2): 35-42.		
Methods	Factorial plot experiment with various treatments (including asulam application) compared to a control.		
Population	U20 on a site that was previously (cf 40 years) lowland heath.		
Intervention and Co interventions	Asulam application was trialled after i) litter clearance and ii) litter clearance and ploughing		
Outcomes (frond		Treatment	Control

density m-^{2}).		Mean	n	SD	Mean	n	SD
	Litter removal	9.4	3	No SD	25.3	3	8.65
	Litter removal and ploughing	7.8	3	No SD	25.3	3	8.65
Study design	Factorial experiment (although the control was surrounding vegetation)						
Baseline Comparison	No details of the baseline are presented						
Intra treatment variation	See baseline comparison						
Measurement of intervention and Co-interventions	Asulam application was the primary intervention. However the impact of litter removal prior to spraying could have had a biggere impact than the use of asulam.						
Replication	Three replicate areas were assessed within the area denuded of litter and compared to surrounding untreated vegetation.						
Parameter of abundance	Frond density was extracted but frond dry weight is also presented						
Size of experimental area	15 x 5m subplots were used for application of asulam. Rhizome ingression may have impacted the results.						
Notes	This experiment is really concerned with heathland restoration. Litter was stripped exposing mineral subsoil for colonisation by lowland heath. Re-invading bracken was treated with asulam in three replicates (as part of a factorial experiment) and compared to totally untreated bracken. The baseline difference between treatment and control after litter stripping but prior to asulam application will therefore have a big impact on the result and limits its applicability with respect to the effectiveness of asulam on marginal land. The two asulam treatments (i.e. asulam after litter removal, asulam after litter removal and ploughing) are not independent as they are compared to the same control. Least Significant differences are presented but the treatment sd cannot be approximated from this as i) it is not stated if P is 0.01 or 0.05 and ii) it is not clear if the control mean is included in the differences.						

Study	Lowday, J. E. (1985). Asulam Applied by Rope Wick Applicator for Controlling Scattered Bracken on A Grassland Nature-Reserve. *Annals of Applied Biology* **106**: 90-91.						
Methods	Randomised block experiment with four replicates comparing asulam application once with a rope wick to two passes with a weed wiper and an untreated control						
Population	The population is lowland heath with bracken at 5 fronds per metre.						
Intervention and Co interventions	Interventions are i) asulam application once with a rope wick and ii) two passes with a weed wiper. No details of management of Thetford heath. A 1:1 solution of asulam salts was applied at 40% but the dose per ha cannot be calculated. The mean value from other studies has therefore been used for meta-regression analyses (this is already a down-weighted study as no variance measures are presented).						
Outcomes (frond density m^2).		Treatment			Control		
		Mean	n	SD	Mean	n	SD
	Rope wick	1.3	4	No SD	8	4	No SD
	2 x weed wiper	0.8	4	No SD	8	4	No SD
Study design	Randomised controlled trial						
Baseline Comparison	No significant difference between plots prior to treatment with respect to frond density						
Intra treatment variation	Least Square Difference between plot frond density (5.1, 5.8, 4.9) is 2.6 but there is no information on variance within plots.						
Measurement of intervention and Co-interventions	Asulam application was recorded but details of other management are not provided						

Replication	Treatments were replicated 4 times
Parameter of abundance	Frond density was measured
Size of experimental area	Experimental area was 6 x 6m but only the inner 2 x 2m was sampled preventing rhizome ingression from influencing the results
Notes	Replicated randomised design with validated baseline. However, presentation of LSD for two treatments and one control means standard deviations cannot be ascertained for treatment and control sites. The treatments are not independent as they are compared to the same control.

Study	Marrs, R. H., Pakeman, R.J. & Lowday, J.E. (1993). Control of bracken and the restoration of heathland. V. Effects of bracken control treatments on the rhizome and its relationship with frond performance. *Journal of Applied Ecology* **30**: 107-118.
Methods	Complex factorial experiment looking at the impact of different treatments (including asulam), heathland restoration and number of herbicide applications in two replicate blocks (n=2). The impact of asulam applied once and twice was extracted.
Population	U20 on a Lowland grass heath. The trials were carried out on a dense stand of bracken (26 fronds/ m^2) Weeting heath, UK.
Intervention and Co interventions	Asulam applications
Outcomes (frond density m^2).	see table below
Study design	Well designed factorial experiments
Baseline Comparison	There were no significant differences in standing crop, density or height of bracken fronds between treatments at the start of the experiment (400g/m^2, 26 fronds/ m^2, and 100cm respectively). However with only 4 replicates this could reflect lack of power rather than lack of variation (see Lowday 1984 and 1987).
Intra treatment variation	Standing crop range is presented but it is not reported how replicates varied.
Measurement of intervention and Co-interventions	Application of asulam in 1978 and 1978/1985. Grazing by deer and rabbits
Replication	The factorial plots are replicated twice. Within each plot n=4. It is not clear if this represents the two replicates pooled or not.
Parameter of abundance	Frond density m^2 was extracted but rhizome data is also presented
Size of experimental area	Experimental plots were 10mx7m with 1m buffer zones to account for rhizome ingression
Notes	Well designed experiment. However, extracted data is pseudoreplicated (n=4 rather than 2). There are problems with independence within replicated blocks as the treatments are compared to the same mean. Least significant differences are presented across all treatments therefore treatment and control standard deviations cannot be derived. The same experiment is reported on earlier in: Lowday, J. E. (1984). The Effects of Cutting and Asulam on the Frond and Rhizome Characteristics of Bracken (Pteridium Aquilinum (L.) Kuhn). *Aspects of Applied Biology* **5**: 275-281. Lowday, J. E. (1987). The effects of cutting and Asulam on numbers of

Outcomes (frond density m^2):

	Treatment			Control		
	Mean	n	SD	Mean	n	SD
S1 asulam 1978	26	4	No SD	27.9	4	No SD
S2 asulam 1978 & 1985	8.7	4	No SD	27.9	4	No SD

	frond buds and biomass of fronds and rhizomes of bracken *Pteridium aquilinum*. *Annals of Applied Biology* **110**(1): 175-184.

Study	Paterson, S., Marrs, R.H. & Pakeman, R.J. (1997). Efficacy of bracken (Pteridium aquilinum (L.) Kuhn) control treatments across a range of climatic zones in Great Britain. A national overview and regional examination of treatment effects. *Annals of Applied Biology* **130**: 283-303.
Methods	Randomised controlled trials of various treatments (including asulam application) applied at 6 sites
Population	U20
Intervention and Co interventions	Asulam application. No further details of management are provided
Outcomes (frond density m^2).	(see table below)
Study design	Randomised controlled trials
Baseline Comparison	Details of baselines are not provided but the authors state that experiments were establish in dense uniform bracken stands
Intra treatment variation	No details provided
Measurement of intervention and Co-interventions	Asulam application but no details of land managment
Replication	N=3 at each site
Parameter of abundance	Frond density m^2 was extracted but other data is also presented
Size of experimental area	8 x 8m plots with 1m buffer zone to prevent rhizome ingression
Notes	Randomised experiments with high precision (36 quadrats used to assess each plot) but low replication (n=3) and no solid baseline. Variance measures are not extractable for treatment and control.

Outcomes (frond density m^2):

	Treatment			Control		
	Mean	n	SD	Mean	n	SD
Mull	16	3	No SD	28	3	No SD
Scottish borders	9.3	3	No SD	36	3	No SD
Lake District	10.7	3	No SD	36	3	No SD
Clwyd	8.7	3	No SD	34	3	No SD
Breckland	6.7	3	No SD	35.3	3	No SD
Devon	2.7	3	No SD	16	3	No SD

Study	Holroyd., J., and Thornton., M. E. (1978). Factors influencing the control of bracken with asulam. *Weed Research* **18**: 181-186.
Methods	Randomised controlled trials at three sites investigating the impact of different herbicides applied at different concentrations and times, with and without adjunct, on bracken frond density
Population	Dense U20 stands over U4(?) grassland
Intervention and Co interventions	Asulam application at different concentrations at different times of year (No information on land management for Newlands I site)
Outcomes (log (100*x* +1) frond number per $10m^2$).	(see table below)

Outcomes (log (100*x* +1) frond number per $10m^2$):

Month and kg asulam ai.i/ha	Treatment			Control		
	Mean	n	SD	Mean	n	SD
July 2.2	3.93	3	No SD	5.35	3	No SD
July 4.5	3.94	3	No SD	5.35	3	No SD
July 9.0	4.32	3	No SD	5.35	3	No SD
September 2.2	5.14	3	No SD	5.43	3	No SD
September 4.5	4.53	3	No SD	5.43	3	No SD
September 9.0	3.93	3	No SD	5.43	3	No SD
October 2.2	4.98	3	No SD	5.19	3	No SD

	October 4.5	5.33	3	No SD	5.19	3	No SD
	October 9.0	5.79	3	No SD	5.19	3	No SD
	March 2.2	5.19	3	No SD	5.35	3	No SD
	March 4.5	5.05	3	No SD	5.35	3	No SD
	March 9.0	5.32	3	No SD	5.35	3	No SD
	May 2.2	5.52	3	No SD	5.08	3	No SD
	May 4.5	4.83	3	No SD	5.08	3	No SD
	May 9.0	4.34	3	No SD	5.08	3	No SD
Study design	Randomised controlled trial at Newlands I (control data is not presented for the remaining two sites)						
Baseline Comparison	No formal baseline is presented but the author states that experiments were established in uniform dense bracken						
Intra treatment variation	See baseline comparison						
Measurement of intervention and Co-interventions	Asulam application on different dates with different concentrations. No details of co-intervention						
Replication	N=3						
Parameter of abundance	(log (100*x* +1) frond number per $10m^2$. We cannot back-transform the data as the data on individual replicates is not presented.						
Size of experimental area	Treatment plots were 3.7 x 5.5m therefore rhizome ingression could affect the results						
Notes	This rct has very low replication (n=3) and no established baseline. Controls between months are independent but the different doses are compared to the same control. No variance data is presented. Two additional sites contain relevant data but lack measurements for control sites and cannot therefore be utilised.						

Appendix Two. *Methodological characteristics and outcomes of herbicides other than asulam.*

Herbicide *vs.* control

Study	**Herbicide**	**Methodological characteristics**	**Outcome**
Al-Jaff *et al* (1982)	Glyphosate	Glyphosate applied as Roundup at different concentrations to randomised designed plots of size 7m by 7m. Three replicates of each block were employed. Glyphosate was applied by a knapsack sprayer.	No difference in the density of the bracken was seen during the season of spraying. A reduction was seen 1 year after treatment, but only with the higher concentrations used. After 15 months there was a reduction in rhizome apex numbers, but again, only with the higher concentrations.
Arends and Velthuis	Metsulfuron methyl and glyphosate	Five field trials for metsulfuron methyl of randomised block design. Five replicates were used in trial 1, 4 in trials 2 and 3, and 3 in trials 4 and 5. The first two trials were with hand-held boom sprayers, and the final three with tractor mounted boom sprayer. Plot size was 4m x 15m for trial 1, 5m x6m in trial 2, 6m x 20m in trials 3 to 5. Glyphosate was used for comparison.	Trial 1:application rate of 24g/ha gave good control after 8 months; boom spray and hand gun application gave similar responses. Trial 2: 60g/ha was required to give same control as trial1. Trial 3: Results achieved by metsulfuron methyl better than glyphosate, Trial 4: Acceptable level of regrowth 10 months after treatment, but better results in trial 5.
Conway and Forrest (1959)	4-chloro-phenoxyacetic Acid (4-CPA).	Different concentrations of 4-CPA applied to plots of bracken, size 30m x 4m.	Spraying is more effective than cutting. Spraying young bracken increases the reduction in healthy rhizome tips and frond buds.
Conway and Forrest (1961)	4-chloro-phenoxyacetic Acid (4-CPA).	Different concentrations of 4-CPA applied to plots of bracken at five different locations in Scotland. Field plots were 27.4m x 3.6m. Main exercise is to observe the translocation of the herbicide through the plant.	Damage to the fronds increased with an increase in concentration of 4-CPA.
Cook *et al* 1980	Amitrole (3-amino-*s*-triazole)	Three trials were carried out using a knapsack sprayer at the time of full frond development. Trial 1: Amitrole alone, Amitrole + ammonium thiocynate, Amitrole + oxysorbic 20 + glycerol, oxysorbic 20 + glycerol. Trial 2: Amitrole alone, Amitrole + Sodium iodide, Sodium Iodide, Ammonium	Trial 1: Amitrole + Ammonium thiocynate gave 97% reduction in frond density; Oxysorbic 20 + glycerol only reduced the frond by 4%. Trial 2: Amitrole alone reduced the frond by 66%

		thiocynate. Trial 3: Amitrole alone, Amitrole + varying concentrations of Ammonium thiocynate, Amitrole + potassium thiocynate.	Other treatments gave very little reduction (2 – 7%) Trial 3: Amitrole alone gave 77% reduction. All other treatments gave 94-97% reduction.
Gordon	Ferrous sulphate	1/20 acre plots. 3 plots, 1 sprayed with 10% and 1 sprayed with 15% solution of ferrous sulphate. The third plot was dusted with powdered ferrous sulphate (2/3 cwt)	Slight browning of foliage, no reduction in frond density.
Gordon	Copper sulphate	1/20 acre plots. 2 plots, 1 sprayed with 4% and 1 sprayed with 8% solution of copper sulphate.	Slight browning of foliage, no reduction in frond density.
Gordon	Hydrochloric acid	1/40 acre plots. 2 plots, 1 sprayed with 3% and 1 sprayed with 6% solution of Hydrochloric acid.	Slight browning of foliage, no reduction in frond density.
Gordon	Kainit	1/20 acre plot dusted with powdered kainit (1 cwt)	Slight browning of foliage, no reduction in frond density.
Hodgson (1974)	Sodium 3,6-dichloro-2-methoxybenzoate	Doses of 2, 4 and 8lb/ac were applied to plots 6x 4m in size at three different locations. At the first site there was three sprays applied in mid-July, Early August, and late August, there was no replication. At the second site there was two sprays in early-August and Late August, with three replications, and at site three there was a single spray in mid-July with three replications.	At each site, irrespective of number of sprays 8ib/ac gave over 90% reduction in frond density. The effectiveness of the other concentrations depended greatly on the site.
Gordon	Sulphuric acid	1/420 acre plots. 2 plots, 1 sprayed with 2.5% and 1 sprayed with 5% solution of Sulphuric acid (twice).	An immediate reduction in frond density. After 4 weeks a new crop of bracken emerged. A second spray eliminated the bracken from the plots for the rest of the year (the timescale of the study). A higher concentration had a quicker effect.

Herbicide vs. asulam

Study	Characteristics	Outcome
Oswald et al	Chlorosulforon applied at different dosages to bracken fronds (one trial includes methabenzthiazuron, and one asulam only) in a randomised block design of plot sizes 5 x 2.5m. The trials were replicated three times.	All treatments reduced the number of fronds one year after spraying. The higher doses of chlorosulfuron were most effective – showed greater frond reduction that asulam.
Hamilton	Glyphosate cf asulam – a single treatment area of 20 x 50m was used for each herbicide. Asulam was applied with and without the wetting agent Ulvapron, and glyphosate was applied with the	Glyphosate with the wetting agent performed better (gave a higher reduction in density) than either asulam alone, or asulam with the

	wetting agent.	wetting agent.
Hamilton	Metsulfuron-methyl cf asulam - a single treatment area of 20 x 50m was used for each herbicide. Asulam was applied with and without the wetting agent Ulvapron, and metsulfuron-methyl was applied with the wetting agent.	Metsulfuron-methyl with the wetting agent performed better (gave a higher reduction in density) than either asulam alone, or asulam with the wetting agent.

Follow up after glyphosate application

Study	Characteristics	Outcome
Petrov and Marrs	Initial application of glyphosate on 5 x 5m plots arranged in four replicate blocks. Treatment block 1 was a control and wasn't treated at all. Follow up treatments were 2: none; 3: bracken cut twice yearly; 4: follow up glyphosate treatment; 5: seeding treatment; 6: seeding treatment plus twice yearly cutting. The seeding treatment involved sowing *Festuca rubra* and *Vicia cassubica*.	Where there was neither follow up or seeding treatment control was the poorest with a sustained reduction in density for only 2 years. Most successful treatment was follow up with glyphosate spray or seedling treatment (4, 5 and 6).