A Rapid Evidence Review of the Implications of Not Controlling Bracken with Asulam in Scotland

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Contents

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Summary

This report was requested to better understand the implications of not controlling bracken on biodiversity, rural productivity and public health, where asulam is traditionally used for its control in Scotland.

Asulam, sold under the trade name Asulox, is a relatively narrow-spectrum herbicide that has been the predominant chemical method of bracken control, particularly on rough or steep ground since the 1980s. Authorisation for Asulox was removed in 2012 with all recent use subject to emergency authorisation which has been given on an annual basis.

Emergency authorisation allows a plant protection product to be placed on the market, for limited and controlled use, in a situation where there is not a standard authorisation for that use. If granted, the authorisation period cannot exceed 120 days. Emergency authorisations may only be granted in special circumstances where control is necessary because of a danger to crops, other plants or to the environment, human or animal health. It must also be demonstrated that this danger cannot be contained by any other reasonable means. Applications are assessed against these requirements, including balancing the potential risks and benefits of using the requested product, to decide whether the benefits of granting the authorisation outweigh potential adverse effects.

The manufacturer of Asulox is continuing to seek approval of asulam through the standard process. It may take several years for all the required tests to be carried out. If the known data gaps can be filled, further assessment of asulam would be required to determine if it meets the regulatory conditions for approval.

Not having asulam available would remove the most effective method of bracken eradication, where initial blanket spraying is combined with a proper follow-up programme. It would also mean that control was not possible on steep ground (where the only option is aerial spraying), and it would remove the current forestry management practice of controlling areas of bracken to allow tree establishment. Cutting, while proven to be effective, is restricted to areas with safe vehicle access, is carbon intensive, and takes a longer time to significantly suppress bracken. Recent evidence shows rolling/bruising is ineffective when compared to cutting and asulox treatment. The establishment of woodland and forest habitat along with targeted habitat restoration presents a long-term bracken control option, but asulox is often used as a treatment to allow tree establishment. There is no information on the areas subject to different control methods or on where (aerial) spraying is the only option available. The updating of bracken control guidance is needed whether asulam continues in use or not.

Bracken has been shown to replace other habitats in Scotland, particularly acid grassland and heathland, but there is no data on these trends since 2007. Its presence is often on sites that were previously wooded where its competitive ability and the presence of grazing animals have prevented woodland regeneration. Climate change is highly likely to be behind the continuing expansion of bracken dominance, especially in areas where it was restricted in vigour due to cold temperatures. Combining information on the effectiveness of control and the amount of land treated suggests that past control with asulam has meant that several hundred square kilometres of land are now bracken free that otherwise would be under bracken with consequent benefits for biodiversity and rural productivity.

The expansion of bracken into semi-natural habitats will mean a loss of some of their associated biodiversity. Whilst some bracken stands maintain a woodland ground flora, hill ground taken over by bracken tends to have little value for biodiversity.

There is little scientific evidence available to assess the direct effects of bracken as a source of toxic or carcinogenic compounds within a Scottish context, but assessments at the UK level suggests risks are low. Some studies show that bracken harbours high densities of ticks. However, the evidence on whether levels are higher when compared to other habitats is not clear with tick numbers dependent on the presence of host mammals. More research is needed to assess if its presence and expansion could increase the risk of animal and human tick-borne diseases including Lyme disease.

We have no data on the impact of bracken on rural productivity. It may be possible to get a partial picture of control costs from grant support, but there is an absence of information on lost opportunity costs of bracken replacing grazing resources.

Not controlling bracken in areas without vehicle access where asulam was the previous control method has the following potential negative consequences:

- Limited scope for other methods of control of bracken in rough or steep areas not accessible by vehicles.
- Reliance on less effective bracken control measures and removal of the only effective option known to be capable of eradication.
- Disruption of ongoing follow-up treatment to initial control spraying.
- Implications for woodland and forestry establishment where asulam was a key bracken control method.
- Potential implications for controlling the spread of bracken into acid grassland and health areas with sensitive biodiversity.
- Continuing loss of grazing land.

The potential positive consequences are:

- Removal of the risk of asulam and its breakdown products entering watercourses and soils and resultant potential impacts on non-target species, avoiding ecotoxicological concerns about its use.
- Potential for a negative carbon balance from controlling bracken as the large carbon stores in litter and rhizomes are released.
- Removal of asulox as a control method may drive innovation to find suitable alternatives for control.

A key set of data gaps need filling to provide the basic information for decision making, including:

- Current trends in the area of bracken and transitions between vegetation types.
- Satellite or aerial imagery-based land cover map that include bracken as a separate category. Combining this information with data on terrain slope (e.g., derived from a digital terrain model) would identify areas where aerial spraying is the only control option.
- The long-term effectiveness of asulam-based or cutting-based control programmes.
- A cost-benefit analysis of control for both biodiversity and improvements in grazing.

- It is not known if any of the potential alternative herbicides can be used like asulam in repeated follow-up applications or if they give a long enough window for tree establishment.
- Epidemiological studies of exposure to bracken that could be compared to the risks due to pesticide exposure.
- Tick and tick host densities in different habitats and information on exposure for both humans and livestock.

1. Bracken biology, extent and impacts

1.1. Biology

Bracken is a fern. It is generally accepted that there are two species, *Pteridium aquilinum* (L.) Kuhn in the northern hemisphere and *P. esculentum* (G. Forst.) Cockayne in the southern hemisphere. Subspecies of these two occur, but the UK bracken is almost all *P. aquilinum* subsp. *aquilinum* with some *P. aquilinum* subsp. *pinetorum* in Scottish pinewoods (Wolf *et al*., 2019). Typically, it is seen as a species of woodland plant that the shade of trees generally keeps suppressed. However, with the loss of woodland in many areas it has left bracken as the most competitive species.

Fronds are produced in late spring and die back in autumn. Fronds emerge from buds on a below-ground rhizome network. Even in summer when frond mass is at its highest, usually at least two thirds of the biomass of the plant is below ground in the form of rhizomes. The rhizomes form an extensive network of storage rhizomes at deeper levels and frond-bearing rhizomes nearer the surface.

Stands of bracken vary considerably in height and density. On a deep, well-drained soil at low altitudes bracken can easily grow to 2 m in height and reach above-ground biomass levels of 1.2 kg m^{-2} (12 t ha^{-1}, Le Duc *et al*., 2000). Rhizome biomass can reach 5.1 kg m^{-2} (51 t ha^{-1}) but is usually in the range of 1.5 to 2.5 kg m^{-2} (Le Duc *et al*., 2003). However, on thin soils or at high altitudes, bracken stands thin out. Bracken is rarely found above an altitude of 500 m in Scotland.

Bracken can form almost monospecific stands due to the dense shade created by the fronds in summer and because the dead fronds rot slowly and can form deep layers of litter, particularly in drier parts of the country.

Bracken spreads through the slow growth of the rhizomes. Measured rates are around about 40 cm a year (Pakeman *et al*., 2002). Higher rates have been suggested but these likely represent increases in density rather than growth. Bracken can also spread by spores. Under current conditions sporing is infrequent in Scotland and spore establishment and growth is rare; in an experiment attempting to establish plants from spores, there was no establishment in grassland that had been burnt, sprayed or had the vegetation removed (Wynn, 2002). All current stands must have established from spores at some point since the last glaciation, but it appears that it requires significant disturbance to do so (Oinonen, 1967).

1.2. Extent in Scotland and the UK

There are no recent estimates for the extent of bracken in Scotland. Digital products such as UKCEH's Land Cover Map[1] and Space Intelligence's Scotland Landcover map[2] do not map bracken as a separate class, instead including it within a wider grassland class. Early versions of Land Cover Map tried to separate bracken out but there are substantial difficulties in doing this and considerable differences were apparent between the satellite derived data and the ground surveys (Pakeman *et al*., 1996).

A combination of satellite and rule-based Geographic Information System produced an estimate of bracken cover for Scotland of 632.5 km^2 (Miller *et al*., 1990), in an assessment of

[1]https://www.ceh.ac.uk/data/ukceh-land-cover-maps
[2]https://www.space-intelligence.com/scotland-landcover/

the ‘bracken problem’ for the then Scottish Office. Subsequently, the approach was developed to identify geographic niches within which bracken can be expected to be located, based on soil, climate, land use, and of low or high density of cover. The maximum area of the niche for bracken presence was estimated to be 6,036 km^2, or 7.75% of Scotland’s land area (Birnie *et al.*, 2000). Comparing that niche with the area mapped as ‘good rough grassland’ in the Land Cover of Scotland 1988 (MLURI, 1993) showed that c.70% of the national total falls within the bracken niche. (Birnie *et al.,* 2000).

The most recent estimate of bracken cover is from the Countryside Survey 2007 which estimates that 1,320 km^2 (1.6 %) of Scotland is covered with dense bracken (Carey *et al*. 2008). From this source, Scotland level estimates are only available from 1990, but it suggests that there may have been an increase in area between 1990 and 2007. However, the increase between 1998 and 2007 was not significant (Carey *et al*., 2008), whilst there was an overall decline across Great Britain driven by a sharp decline in Wales. Estimates from 1978 and 1984 are based on smaller sample sizes with concomitant higher errors.

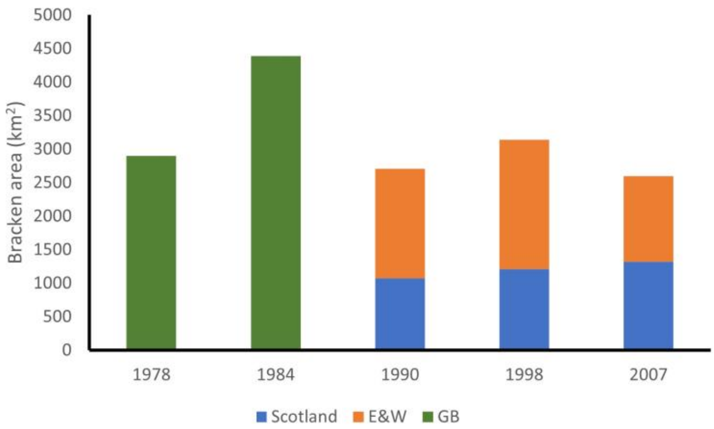

Figure 1. Estimated area of bracken in Scotland, England and Wales (E&W) and Great Britain (GB) from Countryside Survey (Carey et al., 2008).

1.3. Impacts of climate change

A mechanistic model of bracken biology showed that bracken biomass was limited by different factors within different parts of Great Britain (Pakeman & Marrs, 1996). The model predicted that for a rise of 1.4°C, an extension of the frost-free period of 14 days and an increase in evapotranspiration (a measure of increased drought) of 10%, then bracken biomass could increase in the central highland by more than 30%, and across much of the north and west of Scotland by more than 15%. Biomass would also increase at higher altitudes. The model predictions suggest that where bracken is currently not dense enough to shade out the understorey, then ongoing climate change could result in substantial biodiversity loss as bracken outcompetes other species (see section “Impacts on biodiversity”).

A number of long-term experiments into bracken control have been maintained. Long-term monitoring of frond density and height at two experiments in the Scottish Borders (Sourhope, 285 m and 315 m above sea level with a restoration target of upland acid grassland) show that the bracken canopy has significantly increased in biomass, which is in line with predictions for this site from the model (Akpinar *et al*., 2023).

1.4. Impacts on human and animal health

Bracken has long been recognised as a risk to animal and human health (Da Costa *et al*., 2012). It contains a range of compounds that are thought to have evolved to protect it from herbivory including the sesquiterpene ptaquiloside (a toxin and carcinogen), cyanogenic glycosides (cyanide is produced during breakdown), tannins (prevent digestion of proteins) and thiaminases (which cause vitamin B1 deficiency).

Bracken is rarely consumed by livestock, usually only when there is no alternative forage. Farmers generally allow animals to forage freely around bracken stands. Livestock that consume bracken show a wide range of disorders including acute bracken toxicity (caused by ptaquiloside), thiamine deficiency, retinal degeneration (also known as “bright blindness”) and a range of cancers, particularly of the upper digestive tract and bladder. The GB Sheep Disease Surveillance Dashboard[3] shows no unequivocal sheep disease caused by bracken, but it lists 52 cases of poisoning by plants since 2012 in Scotland. Eight cases of cattle poisoned by plants were recorded over the same period[4] but it is not possible to link these to a particular plant species. For comparison there were a total of 1.72 million cattle and 6.83 million sheep in Scotland in June 2021[5].

Human consumption of bracken is usually restricted to fronds in the early stages of unfurling, but this is not a tradition in Scotland and this exposure pathway is negligible. Human consumption is linked to higher incidences of oesophageal cancer (Hirayama, 1979). However, there is also the possibility of exposure to carcinogens through inhalation of spores (no strong evidence of association and sporing is rare in Scotland), milk (presence of carcinogens and epidemiological studies, e.g., Alonso-Amelot & Avendaño, 2001), meat (presence of carcinogens, Fletcher *et al*., 2011) and water (presence of carcinogens, Rasmussen *et al*., 2005). Meat and dairy would constitute a risk in Scotland if consumption was restricted to animals with a high dietary exposure to bracken, i.e., repeated local sourcing of the foodstuffs. The vast majority of meat and dairy come from animals with no exposure and the risks are therefore minimal. There are high numbers of private water supplies in Scotland, while some studies have linked exposure via drinking water to some cancers (e.g., Galpin *et al*., 1990) a FERA risk assessment from 2010 suggest that human exposure to bracken toxins via drinking water is low (Ramwell *et al*., 2010).

One concern surrounding bracken and its impact on animal and human health is the potential for bracken stands, because their litter layer offers suitable habitat for high survival, to have high numbers of ticks which carry the sheep diseases louping ill, tickborne fever and tick pyaemia and Lyme disease that affects humans. A number of studies have shown that bracken stands are characterised by high tick densities (Dobson *et al*., 2011; Medlock *et al*., 2012; Sheaves & Brown, 1995) but there is some uncertainty whether tick densities are higher than other upland vegetation types (Tack *et al*., 2011). Ultimately the risks from tick borne diseases depend on the abundance of tick reservoirs such as deer and disease reservoirs, which for Lyme disease includes a number of small mammals such as voles (Gilbert *et al*., 2012). There is no data available to assess the density of these small mammals in different habitats or for use of bracken as a habitat for deer. Lyme disease incidence in Scotland is estimated at 6.8 cases per 100,000 people per year (2008 to 2013 data, Mavin *et al*., 2015), but incidence rates were considerably higher in Highland (44.1 annual case per 100,000. However, tests of donated blood suggest that 4.2 % of the population have been exposed to Lyme disease (Munro *et al*., 2015).

[3] https://public.tableau.com/app/profile/siu.apha/viz/SheepDashboard_/Overview
[4] https://public.tableau.com/app/profile/siu.apha/viz/CattleDashboard/Overview
[5] https://www.gov.scot/publications/results-scottish-agricultural-census-june-2021/pages/3/

1.5. Impacts on the rural economy

There is no recent information on the impacts of bracken on the rural economy, nor any specific past information for Scotland. A report for MAFF (Lawton & Varvarigos, 1989) calculated that bracken cost Least Favoured Area farms in England and Wales £8.9 million per annum at 1988 prices. This is equivalent to £22.6 million today using the Bank of England inflation calculator. The cost of bracken was calculated from a questionnaire that assessed lost opportunity costs of reduced grazing land, veterinary costs and control costs. Costs for Scottish farmers would be of a similar order of magnitude. There is no similar data for the cost of dealing with bracken in forestry situations.

Much of the control carried out in Scotland has likely been supported under the Agri-Environment and Climate Scheme (AECS), but the actual proportion of control funded by AECS is not known. These figures may give an idea of what is spent on bracken control for certain types of land where its use is supported by AECS (heathland, unimproved grassland eligible for basic payments), but would not provide information on the other costs to the rural economy (e.g., dense bracken on walking routes discouraging tourism or recreation).

There are a range of ways of exploiting the bracken resource; it has traditionally been used for animal bedding, but it can be used to produce compost and as a biofuel. However, harvesting is restricted to areas accessible by machinery and there is limited scope for these uses.

1.6. Impacts on biodiversity

Where bracken dominates, invertebrate and vertebrate species richness is generally low, and the species that are supported are usually of limited conservation interest (Pakeman & Marrs, 1992). Vertebrate species such as whinchats that are associated with dense bracken stands are usually present due to the loss of more suitable habitats (Stanbury *et al*., 2022).

In some areas bracken sustains a woodland ground flora with bluebells and violets there is much higher conservation interest. The violets are the food plants of a number of butterflies including the Dark Green, Pearl-bordered and Small pearl-bordered fritillaries, all species that have declined in recent years (Bulman *et al*., undated). Conservation efforts are focussed at maintaining bracken at a suitable density such that the ground flora is not shaded out.

Where bracken dominates in upland heathland and acidic grassland habitats it seen as a considerable threat to the biodiversity. Many bird species associated with these habitats avoid bracken including raptors such as merlin, waders such as curlew, greenshank and golden plover, as well as red grouse. The invertebrate, vertebrate and plant communities of upland heathland and grassland are also far richer than dense bracken stands (Pakeman & Marrs, 1992). There is no information as to the spread of bracken into amenity grassland or its impacts.

1.7. Impacts on carbon

There is the potential for bracken control to release carbon from the large stores of live and dead biomass (litter). In stand level calculations, bracken control resulted in net losses of carbon as litter was not replaced in the short-term (seven years), with cutting twice per year reducing carbon in the litter and vegetation by around a half and following asulam application by a third (Marrs *et al*., 2007). Hence, there is the potential for a trade-off between control to benefit biodiversity or agriculture and retaining carbon within the plant. Long-term studies and studies comparing different vegetation types are needed to assess how this would change with soil development under different communities or the replacement of bracken biomass and litter by tree biomass and litter.

Bracken litter is highly flammable and hence the litter provides a potential issue regarding the starting and spread of wildfires (Taylor *et al.*, 2021). However, there is currently no available data or analysis on the coincidence of bracken stands and wildfire sites.

2. Bracken control

2.1. Cutting

Cutting works by temporarily halting the creation of carbohydrate via photosynthesis and, more importantly, forcing the plant to use reserves of carbohydrate and nutrients to produce new fronds. Successive cutting is needed to deplete these reserves to substantially reduce frond height and density as well as rhizome reserves of carbohydrate, and cutting twice per year is more effective than cutting once per year (Le Duc *et al*., 2000, 2003).

In a long-term study comparing control techniques, 18 years of cutting twice per year reduced rhizome biomass by c. 75%, whilst cutting once per year reduced it by c. 55%; eradication is unlikely through repeat cutting (Marrs *et al*., 1998). In a further study, control measures were ceased after ten years, and the recovery followed through time. It was estimated that cutting twice per year for ten years provided another 13 to 25 years before recovery was complete, whilst cutting once per year saw recovery in 12 to 18 years depending on site (Akpinar *et al*., 2023).

In practical terms cutting is limited to sites with safe access and relatively even ground. This precludes its use on steep ground and anywhere where rocks or other obstructions could damage the cutting equipment. It is also not recommended on historical or archaeological sites where repeated vehicle passes can damage below-ground artefacts.

2.2. Rolling

Rolling, also known as bruising, was used prior to the development of cutting equipment. It has the practical advantage of being faster than cutting and can be applied on ground that could damage a cutter.

There is no evidence that rolling has any effect on bracken performance or on the composition of the vegetation (Milligan *et al*., 2016, Alday *et al*., 2023). It is, however, included in the options for bracken control in the Agri-Environment and Climate Scheme[6] (AECS) and in the supporting guidance[7].

[6] https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/agri-environment-climate-scheme/management-options-and-capital-items/primary-treatment-of-bracken---mechanised-or-chemical/
[7] https://www.ruralpayments.org/topics/all-schemes/agri-environment-climate-scheme/management-options-and-capital-items/primary-treatment-of-bracken---manual/guidance-for-bracken-management/

2.3. Herbicide control

2.3.1. Asulox

The herbicide Asulox contains the active ingredient asulam (Methyl (4-aminobenzene-1-sulfonyl) carbamate). The active ingredient is absorbed by the fronds and translocated throughout the plant. Its main mode of action is to disrupt metabolism within the frond buds and kill them. However, it is not fully effective at killing all buds, leaving some to form the focus of regeneration.

Asulox spraying generally takes place in summer when fronds are fully expanded, but before they start to senesce. Application can be by helicopter, knapsack or vehicle mounted boom spray. Previously weed wiping and drift sprayers were used but they have not been included in the emergency authorisation. Regulations are in place regarding safe use around watercourses with appropriate buffer strips (5 m from ground sprayers, 90 m from aerial sprayers) to reduce the potential for water contamination.

Following a single application of asulam there is apparently good control, but the few fronds produced in the first summer after spraying form the foci of regeneration and rhizome reserves are never seriously depleted (30 – 40 % reduction in mass compared to unsprayed, Le Duc *et al*., 2003). It takes around 8 to 10 years post-spraying for complete recovery (Akpinar *et al*., 2023). In light of this, a strategy has been developed to enhance the effectiveness of control requiring additional application of asulam. Fronds that appear in subsequent years are spot sprayed using a knapsack sprayer. This maintains and extends the initial high level of control and can lead to eradication (Milligan *et al*., 2016). Previous support payments for bracken control insist on follow-up treatments over the course of the payment agreement.

Asulam has been the herbicide of choice for bracken control given that it has a relatively narrow spectrum of impacts on other plants and was seen as having limited impacts on other groups of organisms. Asulam is known to seriously affect other ferns (Rowntree & Sheffield 2005), reduce the growth of some mosses (Rowntree *et al*. 2003), slow the growth of a range of grasses, but only kill a small range of other plants such as docks (*Rumex* spp. Horrill *et al*. 1978). Toxicity data is available[8] for a range of species groups. For mammals and birds, direct consumption effects are seen only at levels above likely exposure from bracken spraying, whilst for honey bees the effects of contact or consumption are judged to be of low risk. The effectiveness of buffer zones to protect water courses has been assessed and likely levels of water contamination are well below the levels where there is a risk to aquatic organisms (Troldborg *et al*. 2013). This relatively narrow spectrum of impacts allowed it to be sprayed from helicopters. It is, however, now considered as a potential endocrine disruptor and it also reduces eggshell thickness in experimental situations.

2.3.2. Regulation of Asulox

Asulox has no current UK authorisation and its active substance, asulam, is not approved in the UK[9]. EU approval expired in 2008, following which an application was resubmitted which resulted in an EU non-approval decision in 2010. EU approval was again sought in 2013 and

[8] http://sitem.herts.ac.uk/aeru/ppdb/en/Reports/42.htm
[9] https://www.ecolex.org/details/legislation/council-directive-91414eec-concerning-the-placing-of-plant-protection-products-on-the-market-lex-faoc018635/

a European Food Safety Authority (EFSA) peer review in 2018 identified numerous data gaps related to endocrine disruptor properties and long-term risk to birds and mammals. The most recent EFSA peer review (European Food Safety Authority (EFSA) *et al*., 2021) highlights the following issues of concern:

- Data gaps relating to assessment of metabolites.
- Data gap for exposure of humans consuming drinking water.
- Data gap for long-term risk to soil organisms.
- Data gap concerning the risk to wild mammals and birds, including the potential for effects on bird reproduction through eggshell thinning, identified as a critical area or concern.
- That asulam is considered to meet the criteria for endocrine disruption in humans for the thyroid (T) modality. An endocrine disruptor is a substance that alters the normal functions of the endocrine (hormonal) system, causing adverse health effects particularly in relation to reproductive and developmental functions.
- Conclusions couldn't be reached on endocrine-disrupting properties for other non-target organisms based on the information available.

Currently use of Asulox to control bracken is done under emergency authorisation which puts strict limits on when it can be purchased, stored and used. Renewal of emergency authorisation is needed each year. The emergency authorisation application is made to the Health and Safety Executive (HSE) as the regulator. The HSE follows a set number of tests that all have to be met for an emergency authorisation to be recommended. Devolved administrations are consulted on the recommendation and can decide whether to accept it and for HSE to inform the applicant or to call in the decision themselves.

The author did not have access to the HSE recommendation when producing this report.

2.3.3. Alternative herbicides

Glyphosate is licensed for bracken control using a weed wiper. It is a non-selective herbicide, meaning it should only be applied to dense stands of bracken that are both accessible to vehicles and which have limited cover of other plant species.

Two other herbicides have recently been trialled as potential large-scale bracken control treatments: Amidosulfuron and metsulfuron methyl (Brown, 2021). Metsulfuron methyl had a high initial impact followed by rapid recovery in addition to having negative impacts on non-target species. Amidosulfuron showed promising results with respect to initial bracken control (asulam 98 % reduction in frond biomass in the year after spraying, amidosulfuron 96 %, but after five years the respective figures were asulam 52% reduction, amidosulfuron 8%, Brown 2021). Amidosulfuron's non-target effects were assessed in a follow-up study (Cook *et al*., 2022) which demonstrated that it had a wider spectrum of effects than asulam, with greater negative impacts on bryophytes and a range of broad-leaved herbs. In addition, amidosulfuron also negatively affected soil invertebrates compared to asulam treated and the control plots.

2.4. Trees

The dense layer of fronds and the accumulated litter make tree regeneration difficult (Humphrey & Swaine, 1997). However, tree planting is a long-term solution to bracken control, but it is usually combined with asulam application to give the trees time to get away before competition from the bracken intensifies (Biggin, 1982). This is included in current guidance[10]. The integration of tree planting and bracken control offers the potential for long-term biodiversity gains alongside possible increases in ecosystem carbon stocks.

2.5. Livestock

There is no evidence that livestock alone can help control bracken and it is thought their preferential grazing of other species has aided the spread of bracken. However, there is evidence that cattle grazing in the years following spraying slows the regeneration of bracken as they trample the sparse new fronds (Williams, 1980).

2.6. Integrated control and restoration

For effective long term control effective habitat restoration post-control is desirable and it is often not considered as part of control planning. A long-term research programme was established by MAFF/Defra to improve understanding on effective post-control habitat restoration (Akpinar *et al*., 2023 is the latest paper to appear). Advice developed during this programme of work identified the need to prioritise areas for control based on the presence or not of understorey vegetation, and to incorporate methods of litter disturbance (raking, burning) with seed addition to restore vegetation (Pakeman *et al*., 2000; Alday *et al*., 2013). Relying on natural regeneration is slow and potentially results in unwanted outcomes such as communities dominated by mosses (mainly *Campylopus introflexus*) or grasses (mainly *Deschampsia flexuosa*) rather than the previous heather-dominated communities (Pakeman *et al*., 2005). There is evidence that successful restoration can slow the regeneration of bracken (Milligan *et al*., 2018). This prioritisation process and integration of restoration has been lost from recent guidance on bracken control. The current guidance also needs updating in light of recent scientific publications.

[10] https://www.ruralpayments.org/topics/all-schemes/forestry-grant-scheme/forestry-grant-scheme-capital-items/bracken-control/

3. Impact of not controlling bracken where asulam is used currently

3.1. Potential spread in Scotland and the UK

Without either recent data on the extent of bracken or long-term monitoring of the success of control it is difficult to be certain of current trajectories of change or the potential for spread. Models predict that bracken stands over much of Scotland will become denser, especially at higher altitudes. Actual spread is slow (c. 40 cm a year), but it appears that bracken will spread as it goes from a subordinate species to a dominant one.

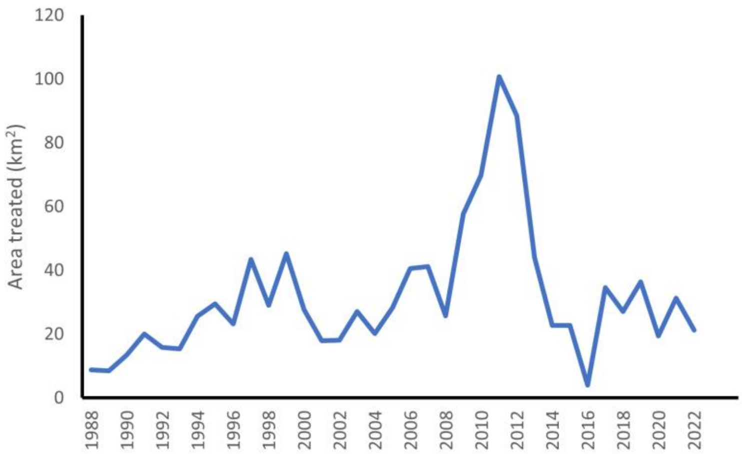

Figure 2. Area of aerial spraying of asulam in Scotland (km^2) from 1988 to 2022.

A previous look at this issue soon after asulam's approval was removed compared aerial spraying areas and Countryside Survey data to suggest that the use of asulam had reduced bracken coverage but it was still invading new areas[11]. It concluded that the extent of bracken in 2007 could have been up to 50% higher than that found by Countryside Survey if asulam had not been applied. It is, however, difficult to estimate how successful bracken control has been and thus how much land would now be covered by bracken if control had not taken place. A long-term study of the effectiveness of spraying in the North York Moors showed that one third of sites had achieved long-term control, 10% had bracken that had regenerated completely, with the remainder on the path to bracken recovery (Pakeman *et al.*, 2005). There is limited information on how climate change may accelerate (maybe through increased temperatures or reduced frosts) or slow recovery (through increased drought).

In total 1,105 km^2 of aerial spraying has been carried out in Scotland since 1988[12] (Figure 2). Assuming around one third of that has achieved long-term control, then c. 370 km^2 of land is now free of bracken. However, the majority of spraying was done after the Pakeman *et al.* (2005) study when best practice and grant conditions meant that follow up treatment became more common and hence (near) eradication after the initial aerial spraying is more likely. Consequently, the estimate of 370 km^2 could be considered conservative. Current

[11] https://knowledgescotland.webarchive.sefari.scot/briefings/briefings097d.html?id=275
[12] https://pusstats.fera.co.uk/data/current

usage is much less than the 2011 peak with around 2% of bracken in Scotland being sprayed annually, though without recent area data this figure is an approximation.

What is unknown is how much land is controlled using other means such as cutting and how this may or may not have contributed to the large-scale picture. It is also not known how much of the current use of asulam could be replaced by cutting as it is on accessible area and how much land can only be treated by aerial spraying of asulam because it is unsafe for vehicle access.

3.2. Potential impacts on human and animal health

The risks of poisoning and cancers from livestock ingesting bracken depends upon exposure. There appears to be no evidence of cancer types caused by bracken to be present in Scotland and overall levels of plant poisoning are low. Similarly, there is no evidence linking human health to bracken presence in water catchments, and dietary exposure is low. This suggests that with current knowledge, the effects of reducing bracken control where asulam is the only control option would have no impact on diseases caused by direct exposure to bracken.

The literature suggests that tick densities can be high in bracken. Climate change is allowing ticks to spread northwards and to be found at higher altitudes. This extends the areas where people and animals can be exposed to infective ticks and thus bracken spread and recovery could play a role in increasing the prevalence of human diseases such as Lyme disease and animal diseases such as louping ill (Bouchard *et al*., 2019; Gilbert, 2021). Consequently, not controlling bracken in some areas potentially promotes tick habitat, although the data on this is equivocal and more studies of tick-habitat associations and where humans acquire infected ticks are required to be sure of this point.

3.3. Potential impacts on rural productivity

Given the paucity of information regarding the impacts of bracken on rural business incomes it is difficult to identify how much limiting bracken control in certain areas may affect them. However, with climate change likely to be driving the increase in bracken expansion (Pakeman & Marrs, 1996) the lack of some control means there is likely to be a loss of grazing resources across upland grasslands and heathlands. At an individual holding level bracken may be a significant impact on the area of grazing land available, but at a national scale bracken problems are associated with relatively unproductive land (upland grassland and heathland) and hence economic losses are likely to be relatively small. In addition, reduced use of asulam as a control option might mean that the small number of companies who carry out bracken spraying withdraw from the market.

Using data available at the time, Birnie (1985) estimated the cost of eradication in Scotland would be approximately £80 million, which compare to the grant assistance at the time of c.£135 000 per annum.

3.4. Potential impacts on biodiversity

Countryside Survey (Carey *et al*., 2008) demonstrated the continued replacement of heathland and grassland habitats by dense bracken. If this pattern has continued there will have been ongoing loss of these habitats with their associated diversity since the last survey in 2007. This will be exacerbated by climate change driving increases in bracken vigour (Pakeman & Marrs, 1996).

Where tractor access is difficult or unsafe then it would be difficult to develop any restoration programme for open habitats. Asulam is also a key part of bracken control during woodland planting and as bracken tends to grow in areas very suitable for woodland restoration, a lack of this control method could hamper woodland expansion targets.

4. Conclusion

4.1. Synthesis

There are two workable methods of bracken control:

- Cutting gradually exhausts the stand's reserves as new frond production depletes rhizome stores of carbohydrate. However, cutting needs to be frequent and maintained for long periods making it energy intensive, and it can only be done where there is safe vehicle access. It does not appear to eradicate bracken, meaning that a break in cutting will allow regeneration.
- Spraying with asulam prevents the plant producing fronds, resulting in a reduction in rhizome reserves as they are not replenished. However, repeated spraying is necessary; without effective follow-up treatment the few surviving frond buds become foci of regeneration and stands regenerate. However, with proper follow-up treatment by spraying any regenerating fronds, this method offers the only current option for eradication.

The emergency authorisation of asulam means that bracken control can be carried out on rough or steep ground where bracken is taking over open habitats. Bracken control during woodland establishment is also currently dependent on the use of asulam. It is not known if any of the alternative herbicides would give a long enough time window to allow tree establishment.

Currently, there are no like for like replacement herbicides for asulam as other herbicides have either been demonstrated to be less effective in trials and/or have a wider spectrum of impact. However, studies of alternative herbicides are limited to initial impacts, and it is possible that strategies could be developed to make control cost-effective including integrating follow-up spraying and vegetation restoration. The size of the mark*et al*so means that any new herbicide will have been developed for other problems and deploying it for bracken control would be a by-product rather than a focus of development and testing.

Bracken is a species that is likely to benefit from climate change, model predictions of which are supported by the limited long-term data available. The continuing pressures on biodiversity and, potentially, rural business that increased bracken vigour will also mean that reducing control options would cause substantial habitat and grazing land loss.

4.2. Knowledge gaps

This review has highlighted a number of knowledge gaps regarding bracken and the impacts of means of control:

- As the large-scale Countryside Survey has not run since 2007, or equivalent Scotland wide multi-date land cover mapping, it is difficult to assess current trends in the area of bracken. It has been recently replaced by a rolling programme of data capture, but outputs so far are limited[13].

- Current satellite-based land cover maps do not provide a separate bracken category. Developing novel ways to accomplish this would be a long-term benefit for assessing spread and control effectiveness. By combining this information with a digital terrain model of suitable spatial resolution, it would be possible to identify areas where control is only possible by aerial spraying due to the steep nature of the ground. An alternative approach could use the 2007 Countryside Survey 1 km square field mapping of land cover in combination with a digital terrain model to estimate how much bracken is on steep ground.
- There is no information on how effective asulam-based or cutting-based control programmes have been, bar one medium-term study on asulam spraying in the North York Moors. Given a substantial part of these have been grant supported it should be possible to identify sites where control has taken place to develop a programme of field visits to assess how effectively grant money has been spent.
- This monitoring of previous control programmes could also be used to develop a cost-benefit analysis of control in terms of both biodiversity and improvements in grazing.
- Information on alternative herbicides such as amidosulfuron is limited to a single application, but it is not known if repeated follow-up applications could have a similar effect to repeated applications of asulam and potentially provide a practical alternative and cost-effective alternative. Amidosulfuron may give a sufficiently long time window for tree establishment, but this would need field testing.
- There is no good quality information on the risks of exposure to bracken in terms of its health impacts. It is outwith the remit of this report to comment on whether epidemiological studies of exposure are possible, and the usefulness of the additional knowledge of the risks. This information could be used alongside that of the risks of exposure to pesticides.
- It would be helpful if there was better knowledge of tick densities in different habitats and long-term information on their densities. Similarly, information on animal tick borne diseases would benefit from linking cases of disease to potential exposure on farms. This would be feasible if there were suitable maps from satellite or aerial imagery, but at present it would need information to come directly from farmers. It is likely to be more difficult to do this for human exposure to tick borne Lyme disease as humans are likely to be exposed in many different habitats.

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[13] https://countrysidesurvey.org.uk/history/2019-plus

6. References

Akpinar, I., Alday, J.G., Cox, E., McAllister, H.A., Le Duc, M.G., Pakeman, R.J. & Marrs, R.H. (2023) How long do bracken (*Pteridium aquilinum* (L.) Kuhn) control treatments maintain effectiveness? *Ecological Engineering*, 186, 106842. https://doi.org/10.1016/j.ecoleng.2022.106842

Alday, J.G., Cox, E.S., Pakeman, R.J., Harris, M.P., Le Duc, M.G. & Marrs, R.H. (2013) Effectiveness of *Calluna*-heathland restoration methods after invasive plant control. *Ecological Engineering*, 54, 218-226. https://doi.org/10.1016/j.ecoleng.2013.01.038

Alday, J.G., Cox, E.S., Santana, V.M., Lee, H., Ghorbani, J., Milligan, G., McAllister, H.A., Pakeman, R.J., Le Duc M.G. & Marrs, R.H. (2023) Recovery of upland vegetation after successful *P. aquilinum* control: long-term effectiveness of cutting, repeat herbicide treatment and bruising. *Journal of Environmental Management*, 342, 118273. https://doi.org/10.1016/j.jenvman.2023.118273

Alonso-Amelot, M.E. & Avendaño, M. (2001) Possible association between gastric cancer and bracken fern in Venezuela: an epidemiologic study. *International Journal of Cancer*, 91, 252-259. https://doi.org/10.1002/1097-0215(200002)9999:9999<::AID-IJC1028>3.0.CO;2-H

Biggin, P. (1982) Forestry and bracken. *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences*, 81, 19-27. https://doi.org/10.1017/S0269727000003225

Birnie, R.V. (1985). An assessment of the bracken problem in relation to hill farming in Scotland. *Soil Use and Management,* 1, 57-60. https://doi.org/10.1111/j.1475-2743.1985.tb00657.x

Birnie, R.V., Miller, D.R., Horne, P.L., Leadbeater, S. & MacDonald, A. (2000) The Potential distribution and impact of bracken in upland Scotland: an assessment using a GIS-based niche model. *Annals of Botany*, Volume 85, Suppl. 2, 53–62. https://doi.org/10.1006/anbo.2000.1112

Bouchard, C., Dibernardo, A., Koffi, J., Wood, H., Leighton, P.A. & Lindsay, L.R. (2019) Climate change and infectious diseases: the challenges: N increased risk of tick-borne diseases with climate and environmental changes. *Canada Communicable Disease Report*, 45, 83. https://doi.org/10.14745/ccdr.v45i04a02

Brown, R.W. (2021) National Bracken Chemical Control Trials 2012 – 2020. Final Summary Report. https://www.brackencontrol.co.uk/downloadfile/17583844?open=true, https://www.brackencontrol.co.uk/downloadfile/17583847?open=true

Bulman, C., Joy, J. & Bourn, N. (undated) Bracken for butterflies. https://butterfly-conservation.org/sites/default/files/habitat-bracken-for-butterflies.pdf

Carey, P.D., Wallis, S., Chamberlain, P.M., Cooper, A., Emmett, B.A., Maskell, L.C., McCann, T., Murphy, J., Norton, L.R., Reynolds, B., Scott, W.A., Simpson, I.C., Smart, S.M. & Ullyett, J.M. (2008) Countryside Survey: UK Results from 2007. NERC/Centre for Ecology & Hydrology, 105pp. (CEH Project Number: C03259) https://nora.nerc.ac.uk/id/eprint/5191/1/N005191CR%20UK%20Results.pdf

Cook, S., Ellis, S., Kelly, S. & Brown, M. (2022) Comparative assessment of risks to non-target plants and soil invertebrates and soil persistence of two bracken herbicides: asulam and amidosulfuron. Report for Natural England, ADAS. https://www.brackencontrol.co.uk/downloadfile/18956263?open=true

Da Costa, R.G., Bastos, M.M.S.M., Oliveira, P.A. & Lopes, C. (2012) Bracken-associated human and animal health hazards: chemical, biological and pathological evidence. *Journal of Hazardous Materials*, 203, 1-12. https://doi.org/10.1016/j.jhazmat.2011.12.046

Dobson, A.D., Taylor, J.L. & Randolph, S.E. (2011) Tick (*Ixodes ricinus*) abundance and seasonality at recreational sites in the UK: hazards in relation to fine-scale habitat types revealed by complementary sampling methods. *Ticks and Tick-borne Diseases*, 2, 67-74. https://doi.org/10.1016/j.ttbdis.2011.03.002
European Food Safety Authority (EFSA) *et al*. (2021) Updated peer review of the pesticide risk assessment of the active substance asulam (variant evaluated asulam ‐ sodium). *EFSA Journal*, 19, e06921. https://doi.org/10.2903/j.efsa.2021.6921
Fletcher, M.T., Reichmann, K.G., Brock, I.J., McKenzie, R.A. & Blaney, B.J. (2011) Residue potential of norsesquiterpene glycosides in tissues of cattle fed Austral bracken (*Pteridium esculentum*). *Journal of Agricultural and Food Chemistry*, 59, 8518-8523. https://doi.org/10.1021/jf201342t
Galpin, O.P., Whitaker, C.J., Whitaker, R.H. & Kassab, J.Y. (1990) Gastric cancer in Gwynedd. Possible links with bracken. *British Journal of Cancer*, 61, 737-740.
Gilbert, L. (2021) The impacts of climate change on ticks and tick-borne disease risk. *Annual Review of Entomology*, 66, 373-388. https://doi.org/10.1146/annurev-ento-052720-094533
Gilbert, L., Maffey, G.L., Ramsay, S.L. & Hester, A.J. (2012) The effect of deer management on the abundance of *Ixodes ricinus* in Scotland. *Ecological Applications*, 22, 658-667. https://doi.org/10.1890/11-0458.1
Horrill, A.D., Dale, J. & Thomson, A. (1978) Asulam – its effects on selected plants, plant communities and animals. Institute of Terrestrial Ecology, Grange-over-Sands.
Hirayama, T. (1979) Diet and cancer. *Nutrition and Cancer*, 1, 67-81.
Humphrey, J.W. & Swaine, M.D. (1997) Factors affecting the natural regeneration of *Quercus* in Scottish oakwoods. I. Competition from *Pteridium aquilinum. Journal of Applied Ecology*, 34, 577-584. http://www.jstor.org/stable/2404908
Lawton, J.H. & Varvarigos P. (1989) Socio-economic aspects of bracken control. University of York, York, UK.
Le Duc, M.G., Pakeman, R.J., Putwain, P.D. & Marrs, R.H. (2000) The variable responses of bracken fronds to control treatments in Great Britain. *Annals of Botany*, 85, 17-29. https://doi.org/10.1006/anbo.1999.1052
Le Duc, M.L., Pakeman, R.J. & Marrs, R.H. (2003) Changes in the rhizome system of bracken subjected to long-term experimental treatment. *Journal of Applied Ecology*, 40, 508-522. https://doi.org/10.1046/j.1365-2664.2003.00818.x
Marrs, R.H., Johnson, S.W. & Le Duc, M.L. (1998) Control of bracken and restoration of heathland. VII. The response of bracken rhizomes to 18 years of continued bracken control or 6 years of control followed by recovery. *Journal of Applied Ecology*, 35, 748-757. https://doi.org/10.1046/j.1365-2664.1998.355346.x
Marrs, R.H., Galtress, K., Tong, C., Cox, E.S., Blackbird, S.J., Heyes, T.J., Pakeman, R.J. & Le Duc, M.G. (2007) Competing conservation goals, biodiversity or ecosystem services: element losses and species recruitment in a managed moorland–bracken model system. *Journal of Environmental Management*, 85, 1034-1047. https://doi.org/10.1016/j.jenvman.2006.11.011
Mavin, S., Watson, E.J. & Evans, R. (2015) Distribution and presentation of Lyme borreliosis in Scotland–analysis of data from a national testing laboratory. Journal of the Royal College of Physicians of Edinburgh, 45, 196-200. https://doi.org/10.4997/jrcpe.2015.304
Medlock, J.M., Shuttleworth, H., Copley, V., Hansford, K.M. & Leach, S. (2012) Woodland biodiversity management as a tool for reducing human exposure to *Ixodes ricinus* ticks:

a preliminary study in an English woodland. *Journal of Vector Ecology*, 37, 307-315. https://doi.org/10.1111/j.1948-7134.2012.00232.x

Miller, D.R., Morrice, J.G. & Whitworth, P.L. (1990) Bracken distribution and spread in upland Scotland: an assessment using digital mapping techniques. In: Thomson, J.A. & Smith, R.T., eds. Bracken biology and management. Sydney: Australian Institute of Agricultural Science. Occasional Publication. 40, 121-132.

Milligan, G., Cox, E.S., Alday, J.G., Santana, V.M., McAllister, H.A., Pakeman, R.J., Le Duc, M.G. & Marrs, R.H. (2016) The effectiveness of old and new strategies for the long - term control of *Pteridium aquilinum*, an 8-year test. *Weed Research*, 56, 247-257. https://doi.org/10.1111/wre.12203

Milligan, G., Booth, K.E., Cox, E.S., Pakeman, R.J., Le Duc, M.G., Connor, L., Blackbird, S. & Marrs, R.H. (2018) Change to ecosystem properties through changing the dominant species: impact of *Pteridium aquilinum*-control and heathland restoration treatments on selected soil properties. *Journal of Environmental Management*, 207, 1-9. https://doi.org/10.1016/j.jenvman.2017.11.013

MLURI (1993) The land cover of Scotland 1988: Final report. Aberdeen, Craigiebuckler: The Macaulay Land Use Research Institute.

Munro, H., Mavin, S., Duffy, K., Evans, R. & Jarvis, L.M. (2015) Seroprevalence of Lyme borreliosis in Scottish blood donors. *Transfusion Medicine*, 25, 284-286. https://doi.org/10.1111/tme.12197

Oinonen, E. (1967) The correlation between the size of Finnish bracken (*Pteridium aquilinum* (L.) Kuhn.) clones and certain periods of site history. *Acta Forestalia Fennica*, 83, 1-51. http://hdl.handle.net/10138/17688

Pakeman, R.J. & Marrs, R.H. (1992) The conservation value of bracken *Pteridium aquilinum* (L.) Kuhn-dominated communities in the UK, and an assessment of the ecological impact of bracken expansion or its removal. *Biological Conservation*, 62, 101-114.

Pakeman, R.J. & Marrs, R.H. (1996) Modelling the effects of climate change on the growth of bracken (*Pteridium aquilinum*) in Britain. *Journal of Applied Ecology*, 33, 561-575. https://www.jstor.org/stable/2404985

Pakeman, R.J., Thwaites, R.H., Le Duc, M.G. & Marrs, R.H. (2000) Vegetation re - establishment on land previously subject to control of *Pteridium aquilinum* by herbicide. *Applied Vegetation Science*, 3, 95-104. https://doi.org/10.2307/1478923

Pakeman, R.J., Thwaites, R.H., Le Due, M.G. & Marrs, R.H. (2002) The effects of cutting and herbicide treatment on Pteridium aquilinum encroachment. *Applied Vegetation Science*, 5, 203-212. https://doi.org/10.1111/j.1654-109X.2002.tb00550.x

Pakeman, R.J., Small, J.L., Le Duc, M.G. & Marrs, R.H. (2005) Recovery of moorland vegetation after aerial spraying of bracken (*Pteridium aquilinum* (L.) Kuhn) with asulam. *Restoration Ecology*, 13, 718-724. https://doi.org/10.1111/j.1526-100X.2005.00091.x

Pakeman, R.J., Marrs, R.H., Howard, D.C., Barr, C.J. & Fuller, R.M. (1996) The bracken problem in Great Britain: its present extent and future changes. *Applied Geography*, 16, 65-86. https://doi.org/10.1016/0143-6228(95)00026-7

Ramwell, C.T., van Beinum, W., Rowbothan, A., Parry, H., Parsons, S.A., Luo, W., & Evans, G. (2010) Ptaquiloside and other bracken toxins: a preliminary risk assessment, Final Report. The Food and Environmental Research Agency, Sand Hutton. https://cdn.dwi.gov.uk/wp-content/uploads/2020/10/27111037/DWI70-2-237.pdf

Rasmussen, L.H., Hansen, H.C.B. & Lauren, D. (2005) Sorption, degradation and mobility of ptaquiloside, a carcinogenic bracken (*Pteridium* sp.) constituent, in the soil environment. *Chemosphere*, 58, 823-835. https://doi.org/10.1016/j.chemosphere.2004.08.088

Rowntree, J.K. & Sheffield, E. (2005) Effects of asulam spraying on non-target ferns. *Botany*, 83, 1622-1629. https://doi.org/10.1139/b05-127

Rowntree, J.K., Lawton, K.F., Rumsey, F.J. & Sheffield, E. (2003) Exposure to Asulox inhibits the growth of mosses. *Annals of Botany*, 92, 547-556. https://doi.org/10.1093/aob/mcg166

Sheaves, B.J. & Brown, R.W. (1995) Densities of *Ixodes ricinus* ticks (Acari: Ixodidae) on moorland vegetation communities in the UK. *Experimental and Applied Acarology*, 19, 489-497. https://doi.org/10.1007/BF00052917

Stanbury, A.J., Tománková, I., Teuten, E.L. & Douglas, D.J. (2022) No evidence that declining Whinchat Saxicola rubetra are currently limited by the availability of apparently suitable breeding habitat within the UK uplands. *Journal of Ornithology*, 163, 273-283. https://doi.org/10.1007/s10336-021-01925-6

Tack, W., Madder, M., De Frenne, P., Vanhellemont, M., Gruwez, R. & Verheyen, K. (2011) The effects of sampling method and vegetation type on the estimated abundance of *Ixodes ricinus* ticks in forests. *Experimental and Applied Acarology*, 54, 285-292. https://doi.org/10.1007/s10493-011-9444-6

Taylor, A.F.S., Bruce, M., Britton, A.J., Owen, I.J., Gagkas, Z., Pohle, I., Fielding, D. & Hadden, R. (2021) Fire Danger Rating System (FDRS) Report. https://www.hutton.ac.uk/sites/default/files/files/publications/SFDRS-Research-Report-Final-15-2-2022.pdf

Troldborg, M., Hough, R.L., Baggaley, N.J. & Dawson, J.J.C. (2013) Aerial Spraying Guidance for the Protection of Watercourses. https://www.crew.ac.uk/sites/www.crew.ac.uk/files/sites/default/files/publication/CREW%20Report%20Aerial%20Spraying.pdf

Williams, G.H. (1980) Follow-up treatments for control of *Pterdium aquilinum*. Proceedings 1980 British Crop Protection Conference – Weeds, 423-428.

Wolf, P.G., Rowe, C.A., Kinosian, S.P., Der, J.P., Lockhart, P.J., Shepherd, L.D., McLenachan, P.A. & Thomson, J.A. (2019) Worldwide relationships in the fern genus *Pteridium* (bracken) based on nuclear genome markers. *American Journal of Botany*, 106, 1365-1376. https://doi.org/10.1002/ajb2.1365

Wynn, J.M. (2002) Factors contributing to the regeneration of bracken (*Pteridium aquilinum* (L.) Kuhn) by spores. PhD. Thesis, University of Manchester.

Tranmire Plain and Grain Beck (near Lastingham, North York Moors) in 1990 and 2005 showing the results of asulam application with subsequent follow-up spraying. Photographs taken from location SE733912 looking north-east.

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