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How long do bracken (*Pteridium aquilinum* (L.) Kuhn) control treatments maintain effectiveness?

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A B S T R A C T

Pteridium aquilinum is a problematic, perennial, invasive species worldwide that poses serious problems in the British uplands. However, there is a lack of knowledge on long-term success in terms of weed control and land improvement. We assessed the effects of six *P. aquilinum*-control treatments at two acid-grassland sites in the Scottish Borders (Sourhope 1 & 2). There were six treatments: (i) untreated, (ii) cutting once-yearly, (iii) cutting twice-yearly, (iv) asulam sprayed in year 1, (v) cutting once in year 1/asulam in year 2, and (vi) asulam in year 1/cut in year 2. The annual cutting treatments were stopped after 9/10 years. We measured the response of three variables over 25/26-years assessing *P. aquilinum*-performance, agricultural-improvement and species richness. We estimated the treatment "effect window", defined as the period over which the *P. aquilinum*-control treatments had a significant effect relative to untreated experimental-controls.

Results were completely different for all variables in the two experiments. At Sourhope 1 the cutting treatments had much longer "effect windows" than the herbicide-based treatments in reducing *P. aquilinum* performance, especially the cut twice-yearly treatment with a 25-year window. At Sourhope 2, the treatment differences were much reduced with the best treatment (cut twice yearly) producing a 13-year window. At both experiments, asulam-based treatments produce a minimum "effect window" of 10 years. Increases in both the agricultural-improvement index and species richness were also obtained at both sites. "Effect windows" for both agricultural-improvement index (TVI) and species richness also showed some improvement; "effect windows" were obtained of 12–20 and 9–20 years for TVI, and 7–17 and 2–10 years for species richness at Sourhope 1 and Sourhope 2 respectively. Species richness declined though time in both experiments.

Cutting, and preferably twice per year, was the most effective treatment but also the costliest, with the most cost-effective approach being a single asulam spray. However, the length of the "effect windows" suggest that repeat-spraying every 10-years is needed. Unfortunately, where the aim is to recover biodiversity interventionist techniques such as seeding will also be needed.

The use of "effect windows" for estimating long-term impact of perennial weed control is novel and may be of use in other situations.

1. Introduction

Methods to assess the control of invasive species have been developed around the world with different levels of success (Hoffmann et al., 2019). However, control of invasive species is becoming especially important from an ecological restoration viewpoint, since perennial weeds can interfere with native species, affecting plant community structure and assembly and causing biodiversity loss (Vitousek et al.,

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1997; Weidlich et al., 2020). Perennial weeds, and especially those that have large, underground, storage structures (e.g. rhizomes), are particularly difficult to control. The manager can usually only have a direct impact on the plant parts that are visible above-ground, and this is a critical barrier for controlling and restoring native communities (D'Antonio et al., 2016).

One such perennial problem rhizomatous species is the fern, *Pteridium aquilinum* (L.) Kuhn. Although a native species in the UK, it is regarded as an aggressive weed species (weed defined as "any plant or vegetation interfering with the objectives of people"; (Mortimer, 1990)), where information on long-term success is sorely needed. It is recognized as one of the most widespread invasive weeds worldwide (Marrs & Watt, 2006), and it is notoriously difficult to control (Marrs & Watt, 2006; Robinson, 2000). Its success depends to a large extent on its large rhizome system, which under temperate climates produces a large above-ground frond biomass, often forming mono-dominant stands during the summer (Williams & Foley, 1976).

From a management viewpoint *P. aquilinum* invasion causes problems for livestock-based, extensive agriculture, conservation, recreation, and game management (Marrs & Watt, 2006; Pakeman & Marrs, 1992). In 1988, *P. aquilinum* was shown to cost £8.8 m to the agricultural economy in the Least Favoured Areas of England and Wales through reducing the amount of available grazing and increasing the costs of stock gathering and veterinary bills (Lawton & Varvarigos, 1989). It is poisonous to grazing animals causing inter alia Vitamin B1 deficiency in mono-gastric animals (Evans, 1976; Evans et al., 1975), and both gastric tract cancers and enzootic haematuria in other grazing livestock (Hirono, 1986; Xu, 1992). Correlative data has suggested that it may be implicated in some human cancers although causation is unproven (O'Connor et al., 2019; Wilson et al., 1998). Ptaquiloside, one of the carcinogens produced by *P. aquilinum*, has been detected in potable water supplies (Clauson-Kaas et al., 2016). Moreover, *P. aquilinum*-dominated vegetation can harbour ticks (Sheaves & Brown, 1995) with their associated diseases affecting both animals and humans (Hudson et al., 1995; Marrs & Watt, 2006). Almost half of farmers surveyed in the LFA in England and Wales reported a *P. aquilinum* problem and 68% favoured a National Control Scheme (Varvarigos & Lawton, 1991).

From a conservation viewpoint, there are a few places where *P. aquilinum*-dominated vegetation provides valuable habitat for species of conservation interest (Bulman & Bourn, 2005; Pakeman & Marrs, 1992; STOG, 1988). However, a general review of the pros and cons of the *P. aquilinum* habitat showed that where it colonizes, the conservation value is generally reduced relative to the communities that it replaces (Pakeman & Marrs, 1992). Moreover, it was regarded as one of the four over-dominant native species that could be linked to reduced species diversity in British broad-leaved woodland (Marrs et al., 2011; Marrs et al., 2013).

There are essentially three ways of managing *P. aquilinum*, through the use of: (1) mechanical techniques, (2) herbicides (Milligan et al., 2016) or (3) biocontrol approaches (Burge & Kirkwood, 1992; Lawton, 1988). The biocontrol methods that have been developed so far have not been widely implemented. Mechanical control needs to be applied annually for a considerable number of years (>10); with this approach the aim is to harvest the fronds continuously, thus depleting the rhizome reserves ((Marrs et al., 1998; Måren et al., 2008; Milligan et al., 2016; Milligan et al., 2018)). For chemical control, a phloem-mobile herbicide is generally used; the herbicide is applied to the fronds and it is then translocated to the rhizomes where it attacks the active and dormant buds used to produce fronds (Veerasekaran et al., 1977a; Veerasekaran et al., 1977b; Veerasekaran et al., 1978). Currently, there are two herbicides used routinely for chemical control; asulam, a selective herbicide, and glyphosate, a non-selective one (Pakeman et al., 2005). For conservation work, the selective herbicide, asulam is preferred as it controls *P. aquilinum* and affects very few other species (Marrs, 1985), although damage to other ferns, docks (*Rumex* spp.), bryophytes and some fine-leaved grasses has been reported (Horrill et al., 1978; Rowntree et al., 2003; Sheffield et al., 2001; Måren et al., 2008). Where asulam is used, there is no visible effect in the year of application but a substantive reduction in frond numbers in the following year, often followed by *P. aquilinum* recovery (Lowday & Marrs, 1992a; Marrs et al., 1998; Milligan et al., 2016; Milligan et al., 2018; Robinson, 2000). Although asulam is deemed to pose a low risk to the environment (Pakeman et al., 2005) and has been licensed for aerial application in the UK, it was withdrawn from use within the European Union (EU) in 2011 (Anon, 2011). The reason for this withdrawal was "a lack of information with respect to metabolites resulting from residues in crop plants". However, because asulam is the only selective herbicide for controlling *P. aquilinum*, its use has been continued in the UK and some other EU-member states under "derogated powers", which requires annual renewal. Asulam use has been possible between 2012 and 2022 via this process in the UK (Bracken Control Group, 2020). Currently, asulam is going through the EU re-registration/approval process. In this study, asulam use pre-dated this issue.

Management of *P. aquilinum* is usually directed towards either agricultural or conservation goals. As there is usually a very depauperate understorey flora under *P. aquilinum*, the first task is to reduce the frond and litter biomass thus allowing light into the soil/litter surface and preferably with some disturbance of the accumulated *P. aquilinum* litter (Lowday & Marrs, 1992a). Thereafter, it is hoped that the ground flora will develop into an open grass or heath community suitable for grazing livestock and with easier access for management purposes. Irrespective of the management goals, or the control method used, the overall aim should be to achieve cost-effective, long-term *P. aquilinum* control and to restore and improve the understorey vegetation composition. There are, therefore, three possible requirements for any weed management/ecological restoration strategy, i.e.:

(1) a long-term reduction in the weed species, here *P. aquilinum*,
(2) an improvement in the quantity and quality of available herbage for grazing by domestic livestock, usually sheep in the UK and,
(3) an increased biodiversity to attain restoration/conservation goals. In the UK uplands, this would usually be an acid grassland or dwarf-shrub-dominated heathland (Barr et al., 1993).

When *P. aquilinum* control is implemented in practice, *P. aquilinum* often recovers quickly (Marrs & Watt, 2006). However, often success is viewed from subjective, visual assessments and there is no attempt to compare the recovery-response to an untreated control. To rectify this, here, we compare the effects of both mechanical and herbicide-based treatments with respect to these three management requirements in two experiments on acid grassland that extend over twenty years on the Sourhope Estate in Southern Scotland. In a previous analysis of these experiments plus another in North Wales, where acid-grassland was the management target, Alday et al. (Alday et al., 2013) showed that three herbicide-based treatments were effective in reducing *P. aquilinum* performance, creating an Alternative Stable State (ASS) of the community over a ten-year period. In the same way, cutting once or twice per year was also effective, but these treatments produced an Alternative State (AS) of the community, i.e. one that was better than the untreated vegetation but as it received an annual treatment could not be judged stable. Given that *P. aquilinum* often recovers relatively quickly after apparently successful treatment (Pakeman et al., 2005; Robinson, 2000), there is a need to know whether these AS and ASS communities were stable, or not, in the longer term, and indeed how long successful control was achieved.

In this study, therefore, we test the longer-term stability of the AS/ASS that had been created over a 10-year period in two of the three acid grassland experiments reported by Alday et al. (Alday et al., 2013), designated Sourhope 1 and 2; the third grassland experiment in North Wales was unfortunately destroyed in 2005 (Cox, 2007). Both experimental designs were identical except that they started in different years (1993 and 1994). They both compared (a) two annual cutting treatments, (b) three one-off herbicide-based treatments, with (c) an untreated control (Alday et al., 2013; Cox et al., 2007; Le Duc et al., 2000; Le Duc et al., 2003). In 2003, when the AS and ASS were detected (Alday et al., 2013), all further treatment was stopped, and the vegetation allowed to develop naturally. We hypothesized that the AS and ASS would not be stable in the longer-term, and the aim here was to determine how long the control/ecological restoration effects would last over a set of three types of response variables: (1) effectiveness of invasive species control measured using *P. aquilinum* frond volume index, (2) agricultural improvement for grazing livestock measured using a total vegetation cover index which excluded *P. aquilinum*, and (3) biodiversity assessed using species richness. We compared the *P. aquilinum*-control treatment responses relative to changes in the untreated controls to provide estimates of temporal "effect windows", i.e., the timescale over which a treatment had an effect. Such estimates are fundamental for the design of long-term, effective, perennial-weed control plans.

2. Methods

2.1. Site location

Two experiments, initially identical but started in different years, were set up on the Sourhope Estate in the Scottish Borders (Fig. S1), designated Sourhope 1 (2° 13′ 17.22″ W, 55° 28′ 31.52″ N; BNG = NT861202, started in 1993) and Sourhope 2 (2° 14′ 42.81″ W, 55° 28′ 57.23″ N; BNG = NT846210, started in 1994) respectively. Sourhope 1 was at an elevation of 325 m and had an aspect of 280° and a slope of 16°, whereas Sourhope 2 was at an elevation of 285 m and had an aspect of 130° and a slope of 22° (Le Duc et al., 2003). There is no information on the length of time that *P. aquilinum* has been a dominant on these sites, but the restoration target was an acid grassland similar to either the *Festuca ovina-Agrostis capillaris-Galium saxatile* (U4) or the *Nardus stricta-Galium saxatile* (U5) grassland communities of the British National Vegetation Classification (Rodwell, 1992). Sourhope 1 was grazed with sheep and cattle and Sourhope 2 by sheep only. In 2008, there was a change in management of the Sourhope Estate from a Research Institute (now James Hutton Institute) to commercial agriculture. This change in ownership resulted in an increased cattle density at Sourhope 1.

2.2. Experimental design

In both experiments, two replicate blocks were delineated before treatment application, and within each, six, *P. aquilinum*-control treatments were applied at the main-plot level (10 m × 40 m). The six control treatments were: (i) untreated (experimental control); (ii) cut once per year in June (Cut1pa); (iii) cut twice per year in both June and August (Cut2pa); (iv) asulam applied in year 1 only (Spray); (v) asulam in year 1 followed by a single June cut in year 2 (SprayCut); (vi) a single June cut in year one followed by asulam spraying in year 2 (Cut-Spray). Generally, single cuts took place in June and second cuts and asulam application in August. Herbicide application was by knapsack sprayer (as Asulox, Bayer CropScience PLC; 4.4 kg active ingredient ha^{-1}; 11 l Asulox in 400 l water ha^{-1}). The *P. aquilinum*-control treatments applied in this study at the main-plot level reflect a combination of 'one-off' (Spray, SprayCut, CutSpray) applied at the start and 'repeated' treatments (Cut1pa, Cut2pa) where treatments were applied annually. Sourhope 1 was started in 1993 and Sourhope 2 in 1994 and cutting treatments were continued until 2003 (see (Cox et al., 2007; Le Duc et al., 2000; Le Duc et al., 2003) for a detailed explanation of the design).

In both experiments, each main-plot treatment was split into two sub-plots, one sub-treatment remaining untreated and the other seeded with a grass seed mix; seeding was applied in August in 1993 at Sourhope 1 and in 1994 at Sourhope 2). All treatments were applied in factorial combination in both experiments, and main-plot and sub-plot treatments were allocated randomly within blocks. After 2003, at Sourhope 2 all treatments were stopped and the *P. aquilinum* allowed to recover, whereas in Sourhope 1, half of each sub-plot was selected randomly for continued treatment, the other half being allowed to recover. Here, we present only data from the Sourhope 1 post-2003 recovery sub-plots and from Sourhope 2.

2.3. Monitoring

Before treatments were applied (year 0; Sourhope1 = 1993, Sourhope2 = 1994), plant species composition and a range of *P. aquilinum* performance variables were measured within three random main-plots in each experimental block to assess within-block uniformity (Cox, 2007). Analysis of variance showed that for both sites there was no significant treatment differences ($P > 0.05$) in frond density, frond length or species number. Sourhope 1, however, had a greater frond density (67 ± 1.9 vs 28 ± 2.0) but a lower mean frond length than Sourhope 2 (39 ± 0.8 vs. 55 ± 2.6), Overall species richness was low, but similar in each experiment (7.1 ± 0.9 vs. 8.11 ± 0.7) before treatments were applied (Cox, 2007).

Thereafter, the plant species composition was monitored annually in late-June from year 1 (1994 for Sourhope 1; 1995 for Sourhope 2 until 2006, and again in 2013 and 2019), i.e., for 25 and 26 years respectively. Quadrats (1 m × 1 m) were placed at three pre-selected random coordinates on 1-m grids within each sub-plot and the cover of all vascular plants, bryophyte and lichen species plus *P. aquilinum* litter were recorded. The $1m^2$ quadrat size is smaller than those recommended for assessments of grassland and heathland communities within the British National Vegetation Classification (Rodwell, 1991; Rodwell, 1992), but they are adequate for assessing the relatively species-poor grassland, heathland and moorland vegetation developing after ecological restoration interventions (Alday et al., 2013; Cox et al., 2008; Harris et al., 2011). To assess *P. aquilinum* performance, all fronds were counted within the central 0.5 m × 0.5 m area, and their length measured (to nearest cm).

2.4. Statistical analyses

All analyses were performed in the R Statistical Environment v.3.5.2 (R Core Team, 2021). The response variables related to *P. aquilinum* control/restoration success were analyzed in three groups: (1) *P. aquilinum*-weed control; five variables providing different assessments of the status/dominance of a *P. aquilinum* stand, these were: frond density (numbers m^{-2}), mean frond length (cm), *P. aquilinum* frond cover (%), *P. aquilinum* litter cover (%) and a derived index of frond volume (FVI) based on the product of the two non-subjective measures (mean frond length x mean frond density). In this paper, we present the results from the frond volume index (FVI) as it combines two important quantitative metrics of frond performance. However, it should be noted that all variables gave very similar results. (2) Agricultural improvement for grazing; this was assessed by calculating a total vegetation index (TVI) by summing the cover of all vascular plants excluding *P. aquilinum*. i.e., those mainly herbs and grasses likely to provide better grazing. (3) Biodiversity improvement; assessed by calculating species richness (number of species m^{-2}) using the 'specnumber' function in the 'vegan' R package (Oksanen et al., 2019), which provided information on the understorey species recovery.

Preliminary analyses using mixed-effects models showed that *P. aquilinum*-main treatments had significant effects through time on the three test response variables (FVI, TVI, species richness) and the temporal effects were a mixture of linear and non-linear responses (Akpinar, 2020). However, the seeding sub-treatment had no consistent treatment interactions through time for any variable (Akpinar, 2020), so all subsequent analyses pooled the data of the two seeding treatments We then used Generalized Additive Mixed Modelling (GAMMs) to model the three response variables to *P. aquilinum*-control treatment through time

(Wood, 2006). GAMM is a semi-parametric and flexible regression technique which is not limited to linear relationships and statistical data distributions making it ideal for modelling the different between-treatment temporal responses detected here (Crawley, 2013). It is often used to predict "softened" smooth functional relationships between the response variable and explanatory variables (Pedersen et al., 2019), with the advantage of no predefined shapes for describing functional relationships. Thus, we used a GAMM-approach to determine the general shapes of the relationships between the three variables with respect to elapsed time for each *P. aquilinum* control treatment. We fitted GAMMs using the 'bam' function in the "mgcv" R package (GAMM; (Wood, 2011)) and plotted the relationships (±95% confidence limits) using the "mgcViz" R package (Fasiolo et al., 2018). Each variable was modelled individually as a function of the following covariates: elapsed time (vector) by treatment (factor), treatment and site (factors). Elapsed time by treatment was modelled with cubic regression smoothing functions and four knots in order to avoid over-fitting the data, but still allowing for unimodal or slightly more complex model fits (Wood, 2011). In these analyses, elapsed time was nested within treatment as a random factor to account for the hierarchical dependency of repeated-measured variables. Smoothness parameters for all covariates and models were chosen using restricted maximum likelihood (REML) selection (Wood, 2011). Details of the fitted GAMM models are presented in Supplementary Appendix: Table S2.

We then define a new concept to help in the restoration of these ecosystems the "effect window", i.e., the time-period over which the applied *P. aquilinum*-control treatments produced a significant positive management difference relative to the respective untreated control. This window was determined by plotting the temporal response from the GAMM analysis for each of the five *P. aquilinum* control treatment at each site alongside its respective untreated control. The points at where the 95% confidence limits showed no overlap were then projected on to the x-axis (years). The approach is outlined in Fig. 1 for one sample treatment (Cut1pa at Sourhope1). This approach provides a conservative estimate in two respects: first through the use of 95% confidence limits around the modelled responses and second by rounding up (start-point) or down (end-point) to the nearest year (see Fig. 1). From a pragmatic management viewpoint, advice would realistically only be needed in year units. As some treatments took time to produce a significant effect the year in which the treatment started and ended are also reported.

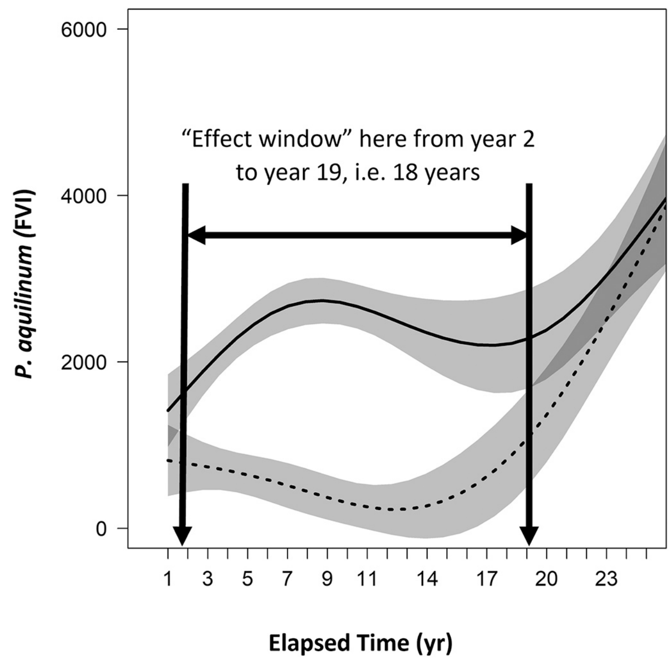

Fig. 1. Calculation of an "effect window". This example is for a GAMM modelled response (±95% confident limits) of the *P. aquilinum* frond volume index (FVI) for the cutting once per year treatment (Cut1pa = dashed) plotted with its untreated "control" (solid line) for Sourhope 1. The point at which the 95% confidence limits do not overlap are determined and projected vertically on to the x-axis to provide an estimate of the start- and end-points of the "effect window" where the treatment is having a desired effect (here a reduction). Where the estimate was between years it was rounded up (start-point) or down (end-point) to provide conservative estimates in whole years. In this example the "effect window" was 18 years, i.e., from year 2 to year 19 inclusive. The statistical information for the model is presented in Supplementary Appendix: Table S2.

3. Results

Overall there were 74 and 117 taxa recoded at Sourhope 1 and Sourhope 2 respectively. Over the course of the entire experiment, the dominant grassland species (>2.5% cover) in the vegetation of the *P. aquilinum*-treated plots of both sites contained *Agrostis capillaris*, *Agrostis vinealis*, *Anthoxanthum odoratum*, *Festuca ovina*, *Festuca rubra*, *Galium saxatile*, *Potentilla erecta*, the moss *Rhytidiadelphus squarrosus* and some *P.aquilinum*. In addition, *Avenella flexuosa*, *Holcus mollis, Nardus stricta* were among the dominant species at Sourhope1 with *Deschampsia cespitosa*, *Poa pratensis* and *Poa trivialis* among the dominants at Sourhope 2. A full species list is presented in Supplementary Appendix: Table S1. A comparison of a successful treatment with the untreated experimental control are presented in Supplementary Appendix: Fig. S2.

3.1. Comparison of temporal change in the untreated experimental-controls

The response of the two untreated experimental-control plots were significant through time at both sites for all three variables (FVI: Sourhope 1, F-value = 11.31, *p*-value<0.001; Sourhope 2, F-value = 10.56; p-value<0.001; TVI: Sourhope 1, F-value = 64.21, p-value<0.001; Sourhope 2, F-value = 9.74; p-value<0.001; species richness: Sourhope 1, F-value = 16.63, p-value<0.001; Sourhope 2, F-value = 22.61, p-value<0.001; Supplementary Appendix: Table S2). There were considerable differences in *P. aquilinum* FVI trends between the untreated experimental-controls at Sourhope 1 and 2 (Fig. 2). Sourhope 1 increased to year 9 after which there was a slight reduction followed by an increase between years 19 and 26 (Fig. 2a). At Sourhope 2, FVI followed a sinusoidal trend with a reduction in cover from the start to year 8 after which there was recovery to a relatively stable asymptote at year 18 which was maintained until year 25 (Fig. 2a). In terms of TVI, both experimental-controls showed similar trends with no differences until year 19, after which Sourhope 1 showed a marked increase compared to Sourhope 2 (Fig. 2b). Species richness showed significant differences in the untreated plots between the two sites, with a greater species richness at Sourhope 2 (Fig. 1c). However, both sites exhibited similar declines in species richness through time, from 11 to 7 species m^{-2} at Sourhope 1 and from 13 to 8 species m^{-2} at Sourhope 2 (Fig. 2c).

3.2. Invasive control treatment effects on P. aquilinum FVI

At both sites all *P. aquilinum* control treatments decreased the FVI significantly relative to the untreated experimental-controls ($P < 0.001$) and produced significantly different responses through time (F-value >4.69, all $P < 0.004$) with the models explaining 39.9% and 47.3% of the deviance for Sourhope and Sourhope 2 respectively (Supplementary Appendix: Table S2). At Sourhope 1, both cutting treatments reduced FVI over the period of application (year 10) and recovery started around year 15; Cut1pa and reached untreated values in year 19 whereas Cut2pa was slower, starting in year 18 and remaining below untreated values at the end of the study in year 26 (Fig. 3a). At Sourhope 2, similar shaped responses were found but recovery was much faster in both

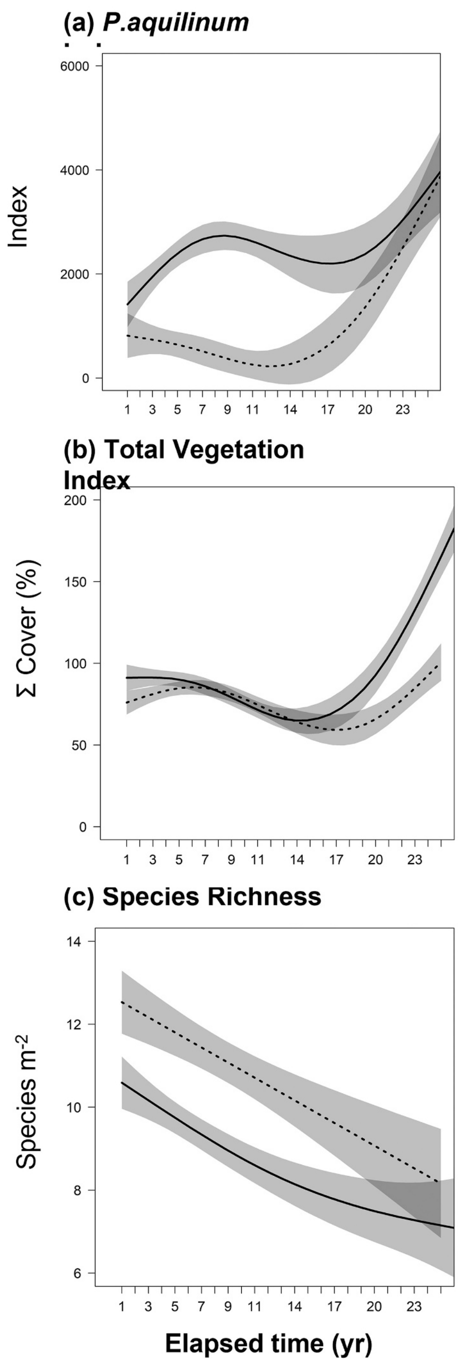

Fig. 2. Modelled GAMM responses (±95% confidence limits) of the three variables in the untreated controls at Sourhope 1 (solid lines) and Sourhope 2 (dashed lines): (a) *P. aquilinum* responses, (b) TVI, i.e. the total vegetation cover of all species except *P. aquilinum*, and (c) species richness. The statistical information of each model is presented in Supplementary Appendix: Table S2.

cutting treatments, a minimum was reached between years 8 and 9, and both had recovered to untreated values by year 14 (Fig. 3b). In contrast, the three herbicide-based treatments (Spray, SprayCut and CutSpray) showed an immediate reduction in *P. aquilinum* cover compared to untreated experimental-controls, but thereafter, there was a consistent recovery in all asulam-treated plots reaching untreated cover values by years 14 to 16 at Sourhope 1 and years 10–13 at Sourhope 2 (Fig. 3).

3.3. Invasive control treatment effects on the agricultural improvement (TVI)

At both sites all *P. aquilinum* control treatments increased TVI significantly relative to the untreated experimental-controls ($P < 0.003$) and produced significant responses through time (F-value >8.49, all $P < 0.001$) with the models explaining 47.3% and 27.5% of the deviance for Sourhope and Sourhope 2 respectively (Supplementary Appendix: Table S2). The TVI was increased significantly relative to the untreated controls at Sourhope1 almost immediately (year 1 or Year 2) and the increase continued to between years 13 and 20 (Fig. 4). At Sourhope 2 the increase took longer to occur (up to year 4) and lasted for a shorter period than at Sourhope 1, to between years 12 and 17 (Fig. 4).

3.4. Invasive control treatment effects on plant species richness

At Sourhope 1, all *P. aquilinum* control treatments increased species richness significantly relative to the untreated experimental-controls ($P < 0.001$) whereas at Sourhope 2 the Untreated, Cut1pa and CutSpray treatments were highly significant ($P < 0.001$), Cut2pa and Spray were intermediate ($P < 0.05$) and $P < 0.01$, respectively) and SprayCut was not significant ($P > 0.05$) (Supplementary Appendix: Table S2). The temporal responses were, however, highly significant at both sites for all treatments (F-value >6.54, all $P < 0.001$) with the models explaining 29.5% and 28.5% of the deviance for Sourhope and Sourhope 2 respectively (Supplementary Appendix: Table S2). At both sites, all treatments showed an overall reduction in species richness through time (Fig. 4). However, all *P. aquilinum*-control treatments showed an increased species richness relative to the untreated experimental-controls for at least part of the study period (Fig. 5) with two types of response: (1) an increased species richness over most of the time-period with a decline to untreated values at the end (Sourhope 1, Cut 1pa, Cut 2pa and SprayCut); (2) a sinusoidal response with an initial increase followed by a reduction to below, or within, untreated values and a subsequent minor increase (all other site x treatment cases) (Fig. 5).

3.5. Success of invasive control treatment – "Effect windows"

The "effect windows" for *P. aquilinum* FVI for all herbicide-based treatments started in the first year at both sites, whereas it took to year 2 at Sourhope 1 and years 3 and 4 years at Sourhope 2 for the cutting treatments to have a significant effect (Fig. 6a). However, the "effect windows" for FVI at both sites lasted longer in the two cutting treatments (Sourhope 1 = years 18–25; Sourhope 2 = 12–13 years) than the herbicide-based treatments (Sourhope 1 = 14–16 years, Sourhope2–11-13 years) (Fig. 6a). The Cut2pa treatment at Sourhope 1 had not reached the untreated values at year 26 so this "effect window" length might be an under-estimate.

For TVI, the impact started in year 1 for four of the five treatments at Sourhope 1; the spray treatment was the exception starting in year 2 (Fig. 6b). At Sourhope 2 the effects started in year 1 for the Cu1pa and CutSpray treatments, year 3 for Cut2pa and Spray treatment and year 4 for the SprayCut (Fig. 6b). At both sites, the cutting treatments had the longest "effect window". At Sourhope 1 the "effect windows" lasted 19 and 20 years for the Cut1pa and Cut2pa treatments respectively, whereas at Sourhope 2 they were much shorter 17 and 14 years respectively (Fig. 6b). At Sourhope 1 the three herbicide-based treatments had "effect windows" of similar length to the *P. aquilinum* FVI reduction; 13–15 years (Fig. 6b), whereas Sourhope 2 only the CutSpray was of similar length to the FVI windows (14 years); the Spray and SprayCut were shorter at 7 and 8 years respectively (Fig. 6b).

For species richness, at Sourhope 1 the impact started in year 1 for the SprayCut treatment, year 2 for the Cut1pa and year 3 for all other treatments (Fig. 6c), whereas at Sourhope 2 it was slower, year 2 (CutSpray and SprayCut), year 3 (Cut1pa), year 4 (Spray and year 6 (Cut2pa) (Fig. 6c). At Sourhope 1, the cutting treatments effects on species

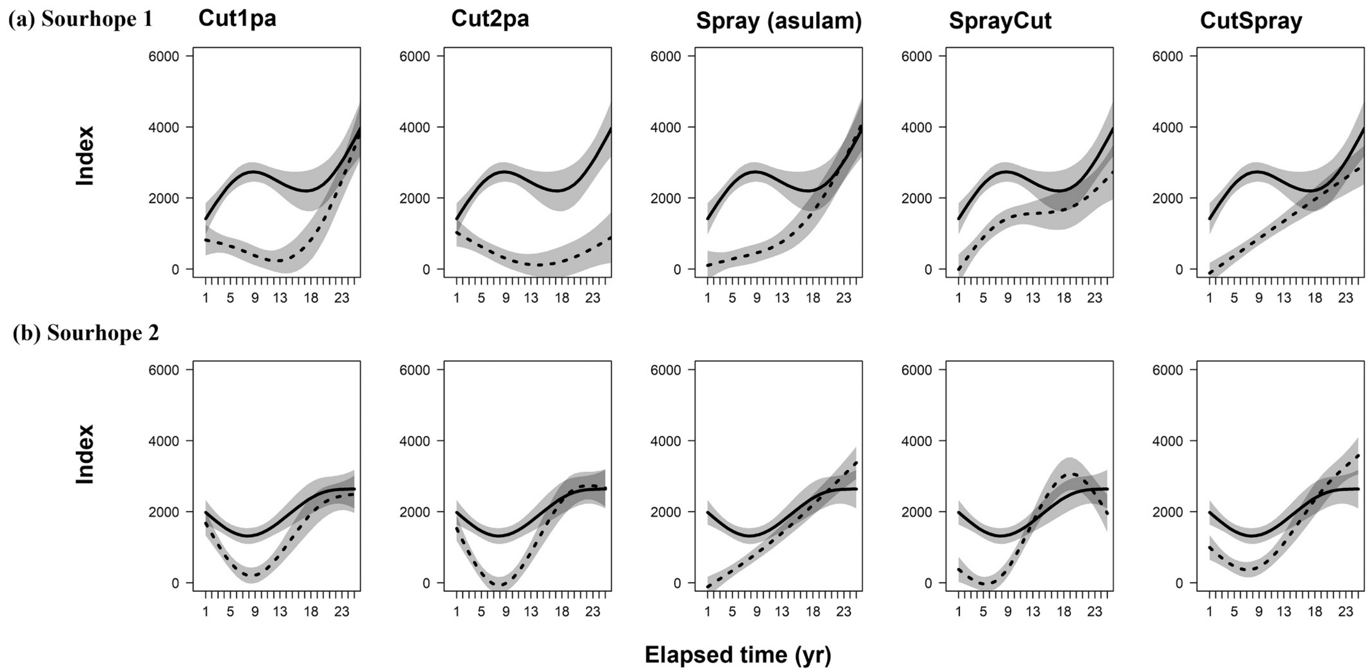

Fig. 3. Comparison of the GAMM modelled responses of the five *P. aquilinum*-control treatments (dashed) on *P. aquilinum* FVI through time relative to untreated controls (black) at two experimental sites, (a) Sourhope 1 and (b) Sourhope 2. Treatments are: Cut1pa, Cut2pa, Spray (asulam), SprayCut and (f) CutSpray. Modelled responses (±95% confidence limits) are presented. The statistical information of each model is presented in Supplementary Appendix: Table S2.

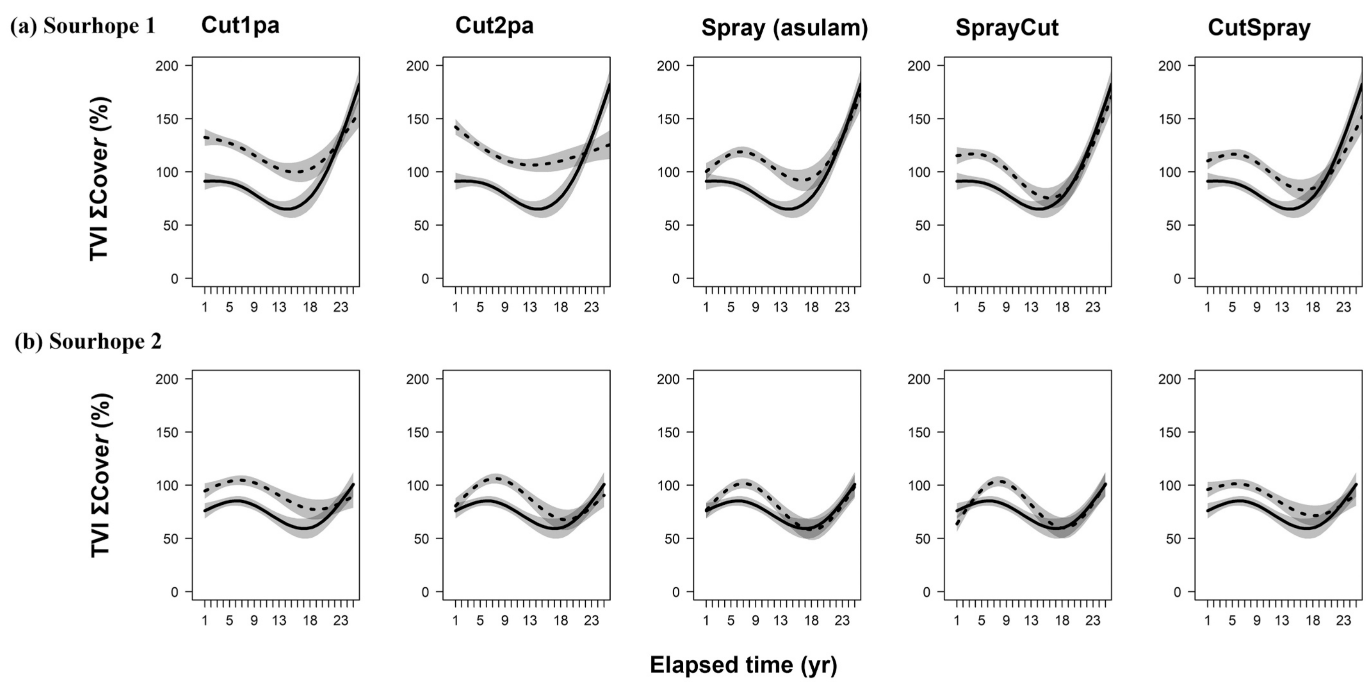

Fig. 4. Comparison of the GAMM modelled responses of the five *P. aquilinum*-control treatments (dashed) on the TVI, i.e. the total vegetation cover of all species except *P. aquilinum* relative to untreated controls (black) at two experimental sites, (a) Sourhope 1 and (b) Sourhope 2. Treatments are: Cut1pa, Cut2pa, Spray (asulam), SprayCut and (f) CutSpray. Modelled responses (±95% confidence limits) are presented. The statistical information of each model is presented in Supplementary Appendix: Table S2.

richness lasted until years 21 and 22 with “effect windows” of 20 years for both treatments (Fig. 6c). The SprayCut “effect window” was intermediate at 19 years whereas the Spray and CutSpray treatments had the poorest effect with “effect windows” of 9 and 10 years (Fig. 6c). The “effect windows” were much shorter at Sourhope 2, the CutSpray and SprayCut were longest (10 years), Cut1pa was marginally shorter at 9 years and the Spray and the Cut2pa were much shorter at 4 and 2 years respectively (Fig. 6c).

4. Discussion

P. aquilinum, is a notoriously difficult weed to control (Marrs & Watt,

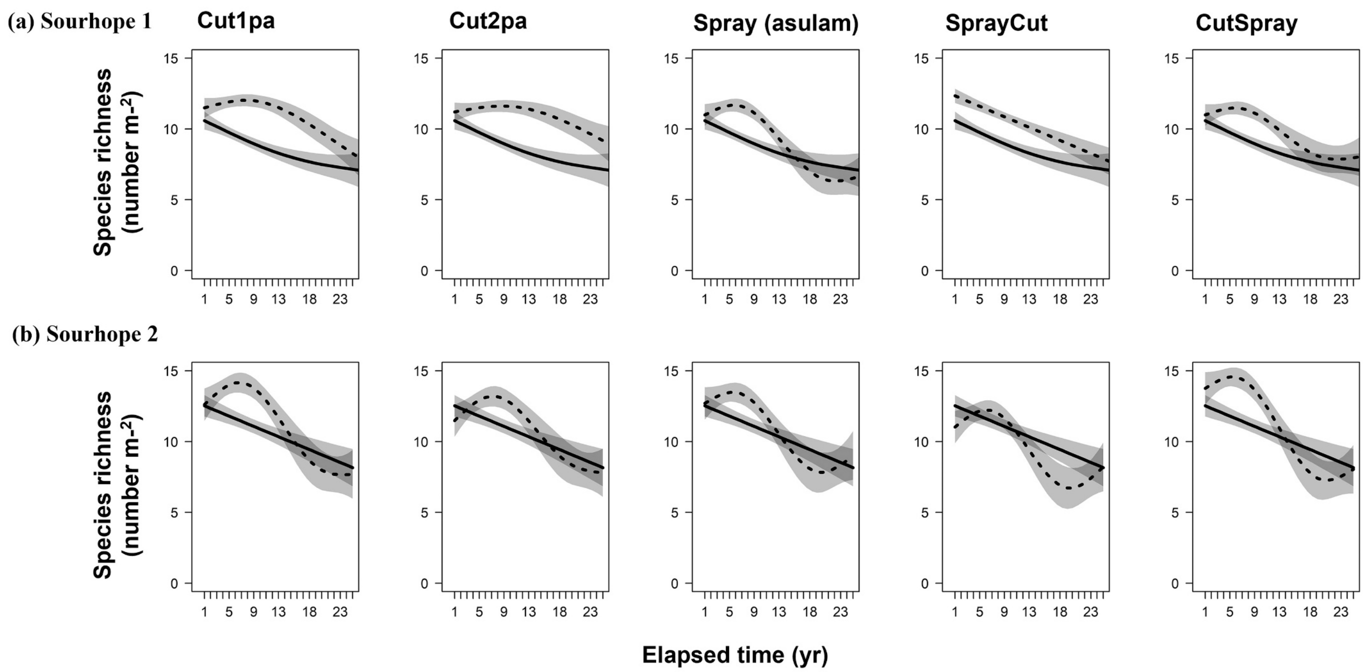

Fig. 5. Comparison of the GAMM modelled responses of the five *P. aquilinum*-control treatments (dashed) on species richness (species m^{-2}) through time relative to untreated controls (black) at two experimental sites, (a) Sourhope 1 and (b) Sourhope 2. Treatments are: Cut1pa, Cut2pa, Spray (asulam), SprayCut and (f) CutSpray. Modelled responses (±95% confidence limits) are presented. The statistical information of each model is presented in Supplementary Appendix: Table S2.

2006; Robinson, 2000), and irrespective of the control methods used there is often a relatively rapid recovery to pre-treatment infestations in the short- to medium-term (Lowday & Marrs, 1992b; Pakeman et al., 2005). In a previous analysis of these two experiments plus another in North Wales, where the management objective was to control *P. aquilinum* and restore acid grassland, Alday et al. (Alday et al., 2013) suggested that good *P. aquilinum* control and restoration of acid grassland could be achieved over a ten-year period. They also recommended and that the herbicide-based treatments was preferred over cutting ones because they required fewer treatment applications; i.e., one (Spray) or two (CutSpray and SprayCut) compared to 10/11 and 20/22 for the Cut1pa and Cut2pa treatments respectively. However, given that *P. aquilinum* is known to recover quickly, there is a need to assess how long these control treatments were effective.

4.1. "Effect windows" for P. aquilinum control

Interestingly, even though the two experiments are on the same working estate, there were significant differences in *P. aquilinum* performance between them, with Sourhope 2 having a greater initial cover than Sourhope 1 and completely different temporal responses (Fig. 2). It seems that between-site differences such as starting the experiments in different years, the effects of different micro-climates, the influence of different stocking rates between the two sites or interactions between all three cause *P. aquilinum* performance differences between the experiments. In this regard, tests of a carbohydrate flux model (COBRA-E, (Pakeman & Marrs, 1996; Pakeman et al., 1994)), where the equilibrium biomass for each site was estimated, showed marked between-site differences (Pottier et al., 2005). Sourhope 1 in particular produced a very poor fit (Pottier et al., 2005). The suggested explanation for the poor fit was micro-climatic, with the results being sensitive to growing season length. These authors argued that the exposed position of Sourhope 1 with a north-easterly aspect was important in restricting *P. aquilinum* productivity at Sourhope 1. As both frond emergence and subsequent growth is controlled by a combination of temperature and late-spring frosts (Lowday, 1983), it is expected that they would impact differentially on both the untreated and treated plots in any given year.

The initial asulam spray treatment showed faster control than the cutting ones which took three to five years to show significant reductions but the two cutting treatments produced longer "effect windows" than the herbicide-based ones at both sites; results similar Milligan et al. *(Milligan et al., 2016; Milligan et al., 2018)*. The between-site differences were, however, maintained in the treatment responses; with "effect windows" of 18 and 25 years at Sourhope 1 but only 12 and 13 years, at Sourhope 2 for the Cut1pa and Cut2pa treatments respectively. The Cut2pa treatment produced a much longer window than Cut1pa at Sourhope 1 (7 years), but only one year at Sourhope 2. In theory, this suggests the Cut2pa treatment should be selected for most effective control rather than Cut1pa, however, the additional costs of the Cut2pa treatment will limit its adoption in practical control strategies (Taylor & Hastings, 2004). In contrast to the cutting treatments, the herbicide-based-treatments had shorter "effect windows" for *P. aquilinum* cover at Sourhope 1 (14–16 years) but the difference was less marked at Sourhope 2 (10–13 years). The potential benefits of combined cutting and herbicide treatments as suggested by (Lowday & Lakhani, 1987)) were not confirmed here, with marginal benefits (+ 2 years) detected at Sourhope 2, but a reduction in effect at Sourhope 2. What is important is that the spray-based treatments for *P. aquilinum*-control had effects that lasted at least 10 years at both sites compared to untreated plots.

4.2. "Effect windows" for agricultural improvement (TVI) and species richness

The impacts of treatment for TVI and species richness were less consistent than effects on *P. aquilinum* TV1 presumably reflecting individual, plot-specific, starting conditions. All *P. aquilinum*-control treatments showed an improved cover of understorey species (TVI) compared to untreated experimental-controls independent of experiment. This positive effect, however, diminished through time with the improved understorey cover lasting longer in the cutting treatments (Sourhope 1) and where the first treatment was a cut (Sourhope 2). What was apparent was the improvement in TVI generally lasted to at least year 10 at both sites for all treatments, although two treatments had shorter

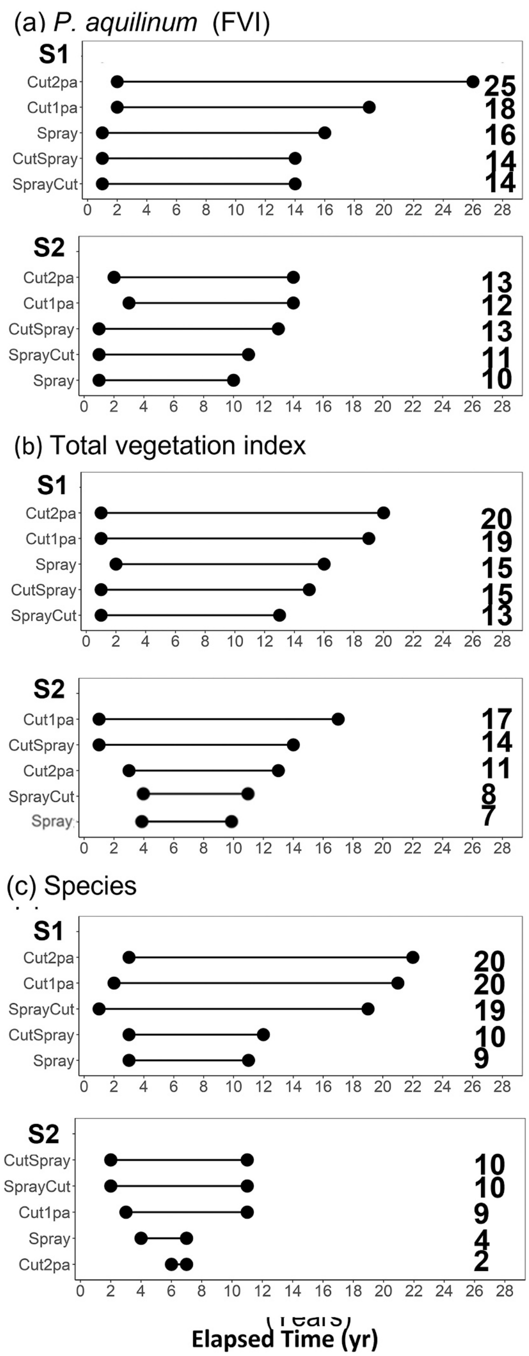

Fig. 6. The "Effect windows" for the five *P. aquilinum*-control treatments at two experimental sites, Sourhope 1 (S1) and Sourhope 2 (S2), with respect to the three response variables, (a) *P. aquilinum* performance index (FVI), (b) TVI, i.e. the total vegetation cover of all species except *P. aquilinum*, and (c) species richness. The treatments are: Cut1pa, Cut2pa, Spray (asulam), SprayCut and (f) CutSpray. The horizontal line represents the length of the "effect window", with the dots indicating the start- and end-point years respectively; the bold numbers at the right are the length of the "Effect windows" in years. Within each panel the treatment "Effect windows" are ranked best to worst, top to bottom. Note for the Cut2pa treatment at Sourhope 1 a significant reduction in FVI was detected at the last sampling in year 26, and hence it is denoted with a? as it could persist beyond the measured period.

"effect windows" because of a slow start. Thus, the agricultural improvement is not maintained for longer than the impact on *P. aquilinum* suggesting that the *P. aquilinum*-dominated community is highly-resilient to these control treatments (Alday et al., 2013).

The species richness results also showed between-site variability with Sourhope 2 being marginally more species-rich than Sourhope 1, although the plant species richness was low in both sites. However, what is striking was the reduction in species richness at both sites over the time-course of these experiments, reflecting similar trends found in repeated surveys in upland Scotland (Britton et al., 2009; Britton et al., 2017; Pakeman et al., 2019; Ross et al., 2012) and trends across Great Britain (Smart et al., 2003a; Smart et al., 2003b; Smart et al., 2006), which have in part been attributed to SO_2 and N atmospheric pollution. In some areas, there is now some evidence that this richness decrease is reversing possibly as a result of reductions in atmospheric SO_2 concentrations (Mitchell et al., 2017; Mitchell et al., 2018), but this improvement was not detected here.

All treatments at both sites brought an improved species richness relative to the untreated experimental-controls for a period, although the between-site variability remained, with Sourhope 1 having much longer "effect windows" than Sourhope 2 for all treatments. It seems that initial richness differences may be because of the exposed nature of the Sourhope 1 site, where understory plant growth and hence competition is reduced relative to the more sheltered Sourhope 2 (Pottier et al., 2005), however, the real cause remains to be determined. At Sourhope 1, the Cut1pa and Cut2pa and the SprayCut treatment maintained a greater species number than untreated experimental-controls for longer than both the Spray and CutSpray treatments, producing "effect windows" of 19–20 years. In contrast, at Sourhope 2 the treatment differences were much less marked with the Spray and Cut2pa treatment being very poor. What is clear is that at best the AS/ASS reported by Alday et al. (Alday et al., 2013) has been maintained in some treatments for a further 10 years but not in others. There was also evidence of a lag in the "effect window" for the herbicide-based treatments, suggesting that the richness increase took place some years after the initial reduction in *P. aquilinum*.

Essentially, at best, the treatments provided a slowing down of the loss in species richness detected in the untreated experimental-controls, which is one of the main aims of invasive species control (Mollot et al., 2017). Moreover, even though a seeding treatment was included in these experiments (Alday et al., 2013), our results detected no consistent improvement in richness through time (Akpinar, 2020). This implies that if there is a management objective to increase species richness (Mollot et al., 2017) then other restoration techniques are needed to obtain greater species establishment and persistence. Such approaches could include seed addition in combination with litter disturbance as this has been shown to be a major impediment to species ingress into the seed bank under *P. aquilinum* (*Ghorbani et al., 2006*), and seedling establishment (Lowday & Marrs, 1992a). Similar works have shown the effectiveness of restoration techniques favouring seedlings establishment such as harrowing, rotavating or burning (Hayes & Holl, 2003; Lowday & Marrs, 1992a; Pywell et al., 2002).

4.3. Limitations to this work

This work is limited as both experiments were located on a single working estate. Moreover, the experiments are not directly comparable as they started in different years; this was deliberate to assess for annual differences in treatment effects associated with differences in climate interacting with treatment applications. There was also a difference in grazing pressures within the estate with Sourhope 1 being grazed by both cattle and sheep whereas Sourhope 2 was grazed by sheep alone; the implications of the heavier cattle trampling effects may have enhanced *P. aquilinum* control (Marrs & Watt, 2006). Irrespective, the use of field experiments that have been monitored over a relatively long time-span are really valuable for improving perennial weed control methods.

Treatment applications were also applied very carefully as experimental treatments, and as such, could not replicate the impacts of commercial applications at a larger scale (Robinson, 2000). No estimate of long-term impacts on the *P. aquilinum* rhizomes have been made; however, effects of treatment on rhizomes in 1999, five and six years after treatment started, showed at all control treatments reduced rhizome mass and that the Cut2pa was most effective at Sourhope 2 and CutSpray at Sourhope 1 (Le Duc et al., 2003). We also accept that the surrogate variables derived for agricultural improvement in our study would have benefitted from a more intensive survey of sward value at the individual species level including assessments of nutrition, digestibility and palatability (Marrs et al., 2020). Lastly, the latter part of the time sequence, post-2006, is based on only two samples in 2013 and 2019, and this means that the length on the "effect windows" can only be viewed as a first-approximation. However, the use of GAMMs have provided a useful technique for estimating the "effect window" of weed control treatments assuming that good temporal data have been collected within properly-designed weed control experiments.

4.4. Practical implications

There is a requirement for practical management applications which are cost-effective that can be applied in a wide variety of situations to develop effective *P. aquilinum*-control/ecological restoration strategies (Cox et al., 2007; Pakeman et al., 2005). When the *P. aquilinum*-treatments were evaluated, all treatments succeeded in reducing the *P. aquilinum* infestation compared to untreated plots and assisted in maintaining an improved sward and a greater species diversity for some years. The clear structural differences between the treated vegetation and the untreated experimental-controls (Supplementary Appendix I: Fig. S2) shows an open vegetation which will allow improved stock gathering, and the improved restored grassland composition described for these experiments by Cox et al. (Cox et al., 2008) will provide better grazing. Through time, *P. aquilinum* recovered and any positive effects on agricultural value and diversity were reduced or had disappeared. However, our estimates of "effect window" lengths suggest that the effects on *P. aquilinum* performance (FVI), potential agricultural values (TVI) and biodiversity may have lasted longer than a manager might suspect after casual inspection, i.e., a latent effect, lasting in some treatments for >20 years (Milligan et al., 2016).

Our results showed that the two cutting treatments tended to produce better overall results than herbicide-based treatments, however, the additional costs of cutting are difficult to justify here. From a pragmatic management perspective, there are three suggested options for treating *P. aquilinum* infestations on similar grasslands, these are:

- Repeat spraying of asulam at approximately decadal intervals. This should keep the "effect windows" open for more time favouring the colonization of more diverse plant communities (Mollot et al., 2017).
- Use of the approach developed by Robinson (Robinson, 2000) where after an initial asulam spray there is an annual spot-spraying of fronds with asulam without respite until extinction. This approach has been shown to be effective (Milligan et al., 2016; Milligan et al., 2018), controlling *P. aquilinum* and favouring native communities.
- Stock the land with cattle immediately after asulam. It is possible that the better *P. aquilinum* long-term control at Sourhope 1 might be associated with cattle stocking, which act to crush emerging fronds (Marrs & Watt, 2006), but this requires further investigation.

Thus, for acid-grasslands *P. aquilinum*-control would involve repeated applications of the herbicide asulam, combined with active restoration approaches such as grazing, harrowing and or seeding. It is possible that repeat asulam applications might produce stepwise benefits for these management requirements. Although the real effectiveness of these combinations needs to be tested in future long-term experiments. What is also clear is that different results can be expected from similar experiments (i.e. between-site variability), even when fairly close geographically and under similar management. Our results confirm the complexity of invasive species control using general recipes (Clout & Williams, 2009).

Finally, our novel concept of "effect windows" proved extremely useful here for analyzing long term experimental data on *P. aquilinum* control, and it also provided user-friendly outputs for practitioners. We suspect similar "effect windows" will prove valuable in studying perennial weed control elsewhere.

Author contribution

This research was started under the auspices of a Defra funded research project on Integrated Bracken control and moorland restoration. The work was planned by MLD, RHM and RJP, field data was collected by MLD, EC and HMcA, and data were analyzed by IA, JGA and RHM. All authors have contributed to data collection and their analyses, the writing of this manuscript, or both.

Declaration of Competing Interest

RHM is President of the Heather Trust (non-executive position, ambassadorial role only), and is an occasional advisor to the Bracken Control Group within the UK; neither organization is aware of this research and they have neither has seen the results or commented on this work. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2022.106842.

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