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Original Article

Amidosulfuron: a potential alternative herbicide to asulam for the control of bracken (*Pteridium aquilinum*) in woodlands

Ian H. Willoughby*, Toni Clarke, Kris Sales

Forest Research, Alice Holt Lodge, Farnham, Surrey GU10 4LH, United Kingdom

*Corresponding author. Forest Research, Forestry Commission, Alice Holt Lodge, Farnham, Surrey GU10 4LH, United Kingdom.
E-mail: ian.willoughby@forestresearch.gov.uk

Abstract

Bracken (*Pteridium aquilinum* (L) Kuhn) is a widespread, vigorous fern which is found throughout the world. While it is native to UK woodlands, it can also outcompete and kill seedlings when mature trees are removed and can harbor disease carrying insects. It is therefore often considered a nuisance weed that needs to be managed. However, non-chemical methods are not always practical or effective, and the herbicide asulam, which was widely utilized to control bracken, is no longer approved for use in Europe. We therefore tested the efficacy and tree tolerance of the herbicide amidosulfuron, in combination with different spray adjuvants, as possible future alternatives for the use of asulam to control problematic bracken infestations in woodland. Although further research is required to confirm crop tolerance, we found that where there are no viable non-chemical options, and where crop trees are otherwise likely to die or be severely supressed, applications of 0.023 kg a.i. ha^{-1} amidosulfuron [e.g. as 0.03 kg ha^{-1} Squire Ultra® (75% w/w amidosulfuron)] plus Mixture B NF® adjuvant at 2% of final spray volume, may be a potentially suitable future replacement for the use of asulam to control bracken in recently planted stands of coast redwood [*Sequoia sempervirens* (D. Don) Endl.], Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco], grand fir (*Abies grandis* Lindl.), Japanese red cedar [*Cryptomeria japonica* (L.f.) D. Don], Macedonian pine (*Pinus peuce* Griseb.), Norway spruce [*Picea abies* (L.) H. Karst.], oak (*Quercus robur* L.), Scots pine (*Pinus sylvestris* L.), silver birch (*Betula pendula* Roth), Sitka spruce [*Picea sitchensis* (Bong.) Carr.], cherry (*Prunus avium* L.), sycamore (*Acer pseudoplatanus* L.), and western red cedar (*Thuja plicata* Donn). However, it is recommended that small scale user trials are always undertaken to test crop safety in local conditions before embarking on any large scale treatment program. Currently amidosulfuron is not approved for use in forestry situations, and there is some uncertainty over the future availability of any amidosulfuron products in the UK beyond 2028.

Keywords: invasive weeds; herbicides; vegetation management

Introduction

Bracken [*Pteridium aquilinum* (L) Kuhn] is a widespread, vigorous species of fern which typically grows to heights of between 0.6 and 1.5 m, but can sometimes reach as high as 4.4 m, and it possesses an extensive underground rhizome system. It is native to the majority of Europe, and is ubiquitous throughout the British Isles. Other members of the genus *Pteridium* are found on every continent on earth apart from Antarctica (Marrs and Watt 2006).

Although bracken forms a desirable natural component of native woodland (Rodwell 1991), when trees are harvested, or when natural gaps in the canopy occur, bracken responds quickly to the increased light levels, with rhizomes spreading rapidly (typically ~1 m a year; Marrs and Watt 2006) and competing strongly for scarce resources with other plants (Harmer *et al.* 2005). Bracken fronds emerge relatively late in the year in May/June, but from July onwards can produce a dense canopy that shades out young trees (Marrs and Watt 2006), with light levels at the forest floor falling to <5% of full sunlight (Gaudio *et al.* 2011), which only a few, highly shade tolerant tree species can survive (Niinemets and Valladares 2006). At the end of the growing season above ground parts die back and collapse, often physically smothering and killing small trees, particularly when the plant litter is weighed down by snow (Humphrey and Swaine 1997, Willoughby *et al.* 2004). In addition, bracken can reduce the amount of rainfall reaching the forest floor by up to 30% (Balandier *et al.* 2022), and is likely to compete for moisture and nutrients throughout the growing season via its extensive rhizome system which, depending on the depth of soil, can extend to 1 m or more below the surface (Watt 1940), although shading and physical smothering are thought to cause the biggest impacts (Humphrey and Swaine 1997). Some woodland plants, particularly if they have a vernal growth habit, can survive beneath a sparse canopy of bracken, taking advantage of the relatively late emergence of fronds in the late spring/early summer that mimic an absent woodland overstory (Marrs and Watt 2006). However, generally where there is a dense, unbroken canopy of bracken, species diversity is reduced (Rodwell 1991) and growth and survival of young trees can be severely impacted (Marrs *et al.* 2000, Harmer *et al.* 2005).

Bracken has the ability to store large amounts of resources in its underground rhizomes; grows rapidly in the late spring/early

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summer; is tolerant of a wide range of site conditions being generally only limited by exposure, severe winter frost and waterlogging; and tends not to be grazed or impacted by insects or other pathogens. These characteristics make it highly competitive with other plant species. In addition, consumption of bracken is linked to urinary bladder cancers in bovines. Genotoxic metabolites are found in milk and meat from bracken fed animals, and exposure to ptaquiloside compounds, which has been suggested to be potentially carcinogenic in humans, is also possible from drinking water collected from infested sites or if bracken sap or spores are inhaled or come into contact with sensitive tissues such as eyes (Marrs and Watt 2006, Costa *et al.* 2024). Bracken is also known to harbor sheep ticks (*Ixodes Ricinus* L.) which can spread the bacterial infection causing Lyme disease (Brown 1995, Sheaves and Brown 1995). Land managers therefore often consider bracken to be a nuisance weed that needs to be controlled, particularly on open moorland and in uncultivated pasture; and also on regeneration sites in forests in Europe, Australasia and North America (Burge and Kirkwood 1992).

In pasture or moorland situations local eradication is usually the aim, requiring an initial primary, and follow up secondary treatments, and then the establishment of an alternative ground cover (Brown and Robinson 1997, Marrs and Watt 2006). By contrast, in forests the objective is normally only to supress bracken long enough to allow young trees to establish, which usually happens within 3–5 years (Willoughby *et al.* 2004).

Cutting, pulling, crushing, and whipping of individual fronds, can all weaken bracken if they are repeated over a sufficiently long period of time (5–10 years) (Brown and Robinson 1997), but such methods are unlikely to be practical or cost effective on a large scale in woodlands, or once trees are planted. However, on recently felled restock sites where bracken has yet to encroach, when combined with "hot planting" as soon as possible after harvesting, repeated, annual, mechanical control to prevent dead fronds smothering young trees may in some instances be sufficient to allow trees to establish, although it remains a relatively costly option.

Reductions in bracken cover are, in theory at least, possible through cultivation before tree planting. Plowing can be used to cut bracken rhizomes and bring them to the surface, where they are exposed to frost damage (Snow and Marrs 1997), and on shallow soils pigs have sometimes been used to achieve similar results (Guest 1996, Brown and Robinson 1997, Guyton 2022). However, plowing, particularly to the depths likely to be required to bring all rhizomes to the surface can cause soil erosion, nitrification and loss of soil carbon, so is nowadays not recommended (Forest Research 2023).

The burning of dead litter by itself provides no check to bracken growth, and can often increase its vigor (Brown and Robinson 1997, Marrs and Watt 2006). Organic mulches such as loose laid bark are ineffective, and installing inorganic sheet mulches is usually impracticable since it is very difficult to fix the material sufficiently strongly into the ground to prevent fronds emerging. The use of 1.8 m tall treeshelters may prevent bracken swamping trees when it dies back in the autumn, and make subsequent mechanical or chemical weeding easier to achieve without damaging seedlings. However, treeshelters are not suitable for heavily branched conifers and by themselves will do nothing to alleviate light or moisture competition. Therefore, once a woodland overstory has been removed and light levels have increased, where bracken needs to be controlled to allow trees to regenerate, the use of herbicides is often the only practical, cost effective option (Willoughby *et al.* 2004).

To be effective in controlling bracken, herbicides need to be translocated throughout the plant and kill frond buds on the rhizome. The only two herbicides with this mode of action that have been approved in the UK in recent years for use on bracken are asulam and glyphosate. They are both applied after full frond expansion has taken place but before any dieback of the tips (this typically occurs between mid-July and late September in the UK and Ireland, depending on location), to ensure maximum absorption and translocation into the below ground rhizome system. Used in this way, both of these herbicides can give a reduction in over 95% of the fronds emerging in the following growing season (Marrs and Watt 2006).

Asulam is a selective, translocated, carbamate herbicide, absorbed by leaves shoots and roots, used until relatively recently for the control of some grass and herbaceous weeds in a range of food crops. In the UK it has also been used extensively since the 1980s to control bracken. In pasture and moorland situations aerial application was normally undertaken as the initial treatment, followed up on a much smaller scale by secondary ground based sprays. In forests only ground based sprays were carried out, usually via handheld applicators. Asulam can be applied to all densities of bracken, because even if the spray falls below the canopy of fronds it has little permanent impact on other vegetation (Brown and Robinson 1997, Marrs and Watt 2006). It is also well tolerated by most tree species, even when they are very small and in active growth (Willoughby and Dewar 1995, Willoughby *et al.* 2018, UPL 2021). Asulam was therefore the only practical chemical option for overspraying young trees to release them from competition by bracken in woodlands. However, in 2023 for commercial reasons the manufacturers ceased supporting the product renewal and no further use of asulam is possible in the UK, although it is still sold elsewhere in the world.

Glyphosate is a broad spectrum, translocated, herbicide that has been used since the 1980s for total vegetation control in a wide range of food and non-edible crops. It can give effective control of bracken, and it has the advantage over asulam that it will also have visible effects on fronds soon after it is applied, allowing the treatment of any areas that may have been missed within same growing season (Marrs and Watt 2006). A disadvantage of glyphosate is that it will also kill or damage trees and other non-target vegetation, so in forest situations for the purposes of bracken control it can normally only be safely used as a pre-planting treatment, although in this context it can be particularly useful where mixed weed populations are present.

Given the demise of asulam, and the variable efficacy of non-chemical approaches, it is prudent to look for possible alternative pesticides. Sulfonylurea herbicides such as metsulfuron methyl, thifensulfuron methyl, tribenuron methyl, chlorsulfuron, and amidosulfuron have been reported as being capable of controlling bracken in some circumstances. Of these, amidosulfuron, and mixtures of chlorsulfuron with metsulfuron methyl appear to be most effective, and thifensulfuron the least, although this depends on the spray adjuvants used and the size of the bracken treated (O'Connor *et al.* 1987, West and Butler 1991, Hamilton 1992, West and Lawrie 1993, West *et al.* 1995). Amidosulfuron will not harm grasses (Bayer 2019), and there is also limited evidence that, depending on the rate used, some tree species will tolerate being over-sprayed (Dixon *et al.* 2006, Stokes and Willoughby 2007). It would therefore appear to offer the best prospects for identifying an alternative herbicide to asulam that will control bracken effectively, but crucially that can also be safely used post planting/germination, over actively growing trees.

Table 1. Experiment site details.

	Experiment 1—Efficacy	Experiment 2—Tree tolerance
Location	Yateley Heath, Hampshire, England	Headley Research Enclosure, Hampshire, England
Latitude, longitude	051°18′53″N, 000°51′18″W	051°08′05″N, 000°50′42″W
Elevation (m above sea level)	80	90
Soil type	Podzol[a]	Podzol[a]
Average annual rainfall (mm)	700	700
Degree days >5°C	1829	1840
Design	A randomized block experiment with 3 replicates (blocks) of 4 herbicide treatments and 3 adjuvant treatments (see Tables 2 and 3), giving 36 plots in total. Plot size was 10 m × 10 m, with the central 8 m × 8 m being assessed.	A randomized block design, with 4 replicates (blocks) of 4 herbicide treatments and 3 adjuvant treatments (see Tables 2 and 3), giving 48 plots in total. Each plot contained 21 species, arranged in 21, 3 m × 3 m sub-plots, each species sub-plot containing 10 trees of a single species at 0.5 m × 1.5 m spacing, with 1.5 m between species sub-plots.
Test species	Bracken (*Pteridium aquilinum* (L) Kuhn)	21 tree/shrub species—see Table 4

[a]Podzols are well drained, acid, sandy soils.

Adjuvants are pesticide additives that can improve the efficacy of herbicide applications, and hence open up the possibility of reducing the amount of active ingredient that needs to be applied to kill weeds, which might in turn help to improve crop tolerance. Adjuvants work by a variety of methods, such as improving penetration into leaves, reducing drift, or enhancing spray retention on plant surfaces (Hunsche 2006, Castro *et al.* 2014). When asulam is used to control bracken, both non-ionic surfactants (non-electrically charged, surface acting agents) and oil based adjuvants have been shown to increase the penetration of leaf waxes and improve uptake, as well as improve translocation to underground rhizomes, and hence enhance overall efficacy (Burge and Kirkwood 1992). However, they have not been recommended for application in forestry situations due to concerns that their ability to improve efficacy could in itself make trees more sensitive to damage (UPL 2021). Non-ionic surfactants and methylated vegetable oils can also increase the efficacy of sulfonylurea herbicides (Nalewaja *et al.* 1995a, 1995b). Amidosulfuron applied at 0.045 kg a.i. ha^{-1} in combination with the non-ionic adjuvant Agral®, has been found to be potentially as least as effective as asulam, providing up to 2 years suppression of bracken (West *et al.* 1995). The adjuvant Mixture B NF® (AmegA 2016) is a mixture of hydrophilic (water soluble) and hydrophobic (oil soluble) non-ionic alkoxylated alcohol surfactants. It is thought to act both as a wetter and spreader, and has been used for many years in mixture with glyphosate and other herbicides to improve uptake and efficacy on various difficult to kill forest weed species (Lawrie and Clay 1993, Willoughby 1997, Willoughby *et al.* 2023). Toil® (Interagro 2015) is a methylated rapeseed oil adjuvant, and it is already used in forestry situations to improve the effectiveness of some graminicides (Willoughby and Forster 2022).

In the work reported here we therefore tested the efficacy and tree tolerance of various combinations and rates of amidosulfuron and different spray adjuvants, as possible future replacements for the use of asulam to control bracken infestations.

Materials and methods

Experiment 1—Efficacy

This experiment was established in Yately Heath Forest, in the south of England (see Table 1), in an area that had previously been stocked with Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] high forest which had been harvested in 2013. At the time we established our experiment in 2018, the restock site was covered in a continuous canopy of naturally occurring bracken. Six different herbicide and adjuvant combinations, including untreated controls, were tested for their efficacy in killing bracken (see Tables 2 and 3).

The spray treatments were made on 22 August 2018, to fully unfurled bracken fronds showing no visual signs of senescence. Weather conditions on the day of application were dry and cloudy, with no rainfall for at least 24 h after spraying. Applications were made at a volume rate of 200 l ha^{-1} (for treatment H1) or 1000 l ha^{-1} (for treatments H2 and H3) using Cooper Pegler CP15 knapsack sprayers at 1 bar pressure fitted with AN2.4 Red Polyjet nozzles [BCPC nozzle code (BCPC 2010) D/2.4/1], which gave a flow rate of 2 L min^{-1} with a coarse spray quality to produce a 2 m wide treated swathe. Test applications using water were carried out in an area of bracken adjacent to the experimental plots to ensure that volume rate was sufficient to achieve good coverage through to ground level without run off for the height of the bracken canopy. A dye marker (Signal Blue Spray Pattern Indicator, Precision laboratories, www.precisionlab.com, at a rate of 0.46% of final spray volume) was used with all applications, including the water controls, to help achieve accurate spraying and avoid excessive overlapping of the swathes. Five, parallel, 2 m wide spray swaths were made to fully treat each 10 m × 10 m plot.

A visual assessment of percentage of live bracken cover in the central 8 m × 8 m area of each treatment plot was carried out immediately before spraying, then on 18 July 2019, 47 weeks after spraying.

Statistical analysis was conducted in R (R Core Team 2023), with graphics produced using ggplot2 (Wickham 2016). An arcsine transformation was applied to the percentage live bracken cover prior to analysis. A linear model was then fitted with bracken cover in July 2019 as the outcome variable, and block, herbicide treatment and adjuvant treatment and their interaction as fixed effects. *Post hoc* tests were carried out on the arcsine transformed values, with *P*-values adjusted for multiple comparisons using the Tukey method (Tukey's Highly Significant Difference) (Lenth 2024). These were used to determine which pairwise comparisons of adjuvant/herbicide treatments were significantly different. Groupings of significant differences between treatments were highlighted using "cld{multcomp}" (Hothorn *et al.* 2008) and back transformed marginal means calculated using the "emmeans" package (Lenth 2024).

Reduction in bracken cover provided by each treatment compared to the untreated control was calculated using the

Table 2. List of products tested.

Active ingredient	Product name and composition	Supplier company	Product type
Alkoxylated alcohol	Mixture B NF® (42.5% polyoxyethylene (3EO) C12-C15 primary alcohol +38.25% w/w polyoxyethylene (7EO) C12-C15 primary alcohol)	www.nomixenviro.co.uk/	Adjuvant
Amidosulfuron	Squire Ultra® (75% w/w amidosulfuron)	www.sumitomo-chemical.co.uk	Herbicide
Asulam	Asulox® (400 g l^{-1} asulam)	www.upl-ltd.com/uk	Herbicide
Methylated rapeseed oil	Toil® (95% w/w methylated rapeseed oil)	www.interagro.co.uk	Adjuvant

Table 3. Experimental treatments.

Treatment code	Treatment details
Herbicides	
H0	Untreated control—water only, no herbicide
H1	4.0 kg a.i. ha^{-1} asulam (as 10 l ha^{-1} Asulox®)
H2	0.023 kg a.i. ha^{-1} amidosulfuron (as 0.03 kg ha^{-1} Squire Ultra®)
H3	0.045 kg a.i. ha^{-1} amidosulfuron (as 0.06 kg ha^{-1} Squire Ultra®)
Adjuvants	
A0	Untreated control—water only, no adjuvant
A1	Mixture B NF® @ 2% of final spray volume
A2	Toil® @ 0.75% of final spray volume

Notes: H1: Standard application rate of asulam as recommended on the Asulox® product label (UPL 2021) for killing bracken in forestry situations, and is included here as an "active control". H2: 50% of the maximum application rate of amidosulfuron permitted on the Squire Ultra® product label (Bayer 2019). H3: Maximum application rate of amidosulfuron permitted on the Squire Ultra® product label (Bayer 2019). A1: Standard application rate of Mixture B NF® as recommended on the product label (AmegA 2016) for use in mixture with herbicides to increase efficacy. A2: Standard application rate of Toil® as recommended on the product label (Interagro 2015) for use in mixture with herbicides to increase efficacy.

back transformed means at the July 2019 assessment date. Based on the calculated percentage reduction in live cover an indicative 'susceptibility rating' was then assigned, following the terminology used on UK plant protection product labels (i.e. susceptible; moderately susceptible; moderately resistant; resistant) (HSE 2020), but utilizing a slightly more conservative scale to derive the ratings, reflecting the fact that our study was repeated less often than would normally be the case for a full biological dossier submitted for product registration. See Table 5 for further details.

Experiment 2—Tree and shrub tolerance

The second experiment was established at Headley Research Enclosure in southern England (see Table 1). The site is enclosed by deer and rabbit fencing, and regularly cultivated and kept weed free. Based on the results from annual soil analysis it is fertilized as necessary to treat any deficiencies in phosphorus and copper, raise soil pH and supply magnesium and calcium.

The tolerance of 20 commonly used forest tree species, and heather [*Calluna vulgaris* (L.) Hull] (see Table 4), were tested for their tolerance to the same six herbicide and adjuvant combinations as used in Experiment 1 (see Tables 2 and 3).

The trees and shrubs were planted in February/March 2021 into weed-free, rotovated ground. The plants, which were 1–2 year old transplants, were 20–80 cm in height with root collar diameters of 2–6 mm, depending on species, at the time of establishment. They were irrigated regularly after planting with the aim of preventing water deficits. However, in some instances there was occasional, localized failure of the irrigation equipment during the growing season which may have led to periods of water stress. The extent of poor irrigation coverage was therefore recorded, so it could be accounted for in the statistical analysis as a random factor. Herbicides (1.44 kg a.i. ha^{-1} glyphosate; 0.45 kg a.i. ha^{-1} cycloxydim) were applied as necessary during the first and second growing seasons, as carefully directed treatments avoiding over-spraying any tree or shrub foliage, to supress weed vegetation.

The experimental treatments were carried out on a block by block basis over 3 days, on 19–22 July 2021. There was a very light

Table 4. Tree and shrub species tested in experiment 2 for tolerance to herbicide/adjuvant combinations.

Common name	Scientific name
Beech	*Fagus sylvatica* L.
Cherry	*Prunus avium* L.
Coast redwood	*Sequoia sempervirens* (D. Don) Endl.
Douglas fir	*Pseudotsuga menziesii* (Mirb.) Franco
Grand fir	*Abies grandis* Lindl.
Heather	*Calluna vulgaris* (L.) Hull
Japanese red cedar	*Cryptomeria japonica* (L.f.) D. Don
Leyland cypress	*Cupressus x leylandii* A. B. Jacks. and Dallim.
Macedonian pine	*Pinus peuce* Griseb.
Maritime pine	*Pinus pinaster* Aiton
Noble fir	*Abies procera* Rehder
Norway spruce	*Picea abies* (L.) H. Karst.
Oak	*Quercus robur* L.
Scots pine	*Pinus sylvestris* L.
Silver birch	*Betula pendula* Roth
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Sycamore	*Acer pseudoplatanus* L.
Tingiringi Gum	*Eucalyptus glaucescens* Maiden and Blakely
Wellingtonia	*Sequoiadendron giganteum* (Lindl.) J. Buchh.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western red cedar	*Thuja plicata* Donn

Table 5. Percentage reduction in live bracken cover relative to the untreated control, and indicative susceptibility, 11 months after spraying.

Experimental treatment	Percentage (%) reduction in live bracken cover
H1A0: 4.0 kg a.i. ha^{-1} asulam, no adjuvant	65*
H1A1: 4.0 kg a.i. ha^{-1} asulam, plus Mixture B NF®	87*
H1A2: 4.0 kg a.i. ha^{-1} asulam, plus Toil®	65*
H2A0: 0.023 kg a.i. ha^{-1} amidosulfuron, no adjuvant	1
H2A1: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®	90*
H2A2: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Toil®	47*
H3A0: 0.045 kg a.i. ha^{-1} amidosulfuron, no adjuvant	52*
H3A1: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®	90*
H3A2: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Toil®	78*

Notes: See Table 3 for full details of the experimental treatments, including treatment codes. The value for the reduction in live bracken cover provided by each treatment was calculated as follows:- Percentage reduction in live cover = [(live cover untreated control—live cover herbicide treatment)/live cover untreated control]∗100. The color code used to indicate susceptibility is as follows:-

= Susceptible (S): > 95% control.

= Moderately Susceptible (MS): 80%–95% control.

= Moderately Resistant (MR): 50%–80% control.

= Resistant (R): < 50% control. [a]Significantly ($P \leq 0.05$) less live bracken cover than the untreated control H0 A0.

drizzle for 10 min during the application to Block 1, but otherwise weather conditions were dry and sunny, with no rainfall for at least 24 h after spraying.

Applications were made at a volume rate of 200 L ha^{-1} using Cooper Pegler CP3 and Berthoud 9120X knapsack sprayers at 1 bar pressure fitted with AN20.6 Yellow Polyjet nozzles [BCPC nozzle code (BCPC 2010) D/0.6/1], which gave a flow rate of 0.6 L min^{-1} with a coarse spray quality to produce a 0.6 m wide treated swathe. Test applications using water were carried out in the preceding week to ensure that volume rate was sufficient to achieve good coverage of the tree foliage. A dye marker (Maxwell Precision Spray Pattern Indicator Blue www.amenity.agrovista.co.uk at a rate of 1.3% of final spray volume) was used with all applications, including the water controls, to help achieve accurate spraying and avoid excessive overlapping of the swathes. Two, parallel, 0.6 m wide spray swaths were made to fully treat all ten trees within each sub-plot.

The height, root collar diameter and survival of the ten test trees/shrubs in every species sub-plot was measured before spraying, and at the end of the first (October/November 2021) and second (October/November 2022) growing seasons, representing 3 and 15 months after treatment, respectively.

Statistical analysis was carried out in R (R Core Team 2023), using generalized linear mixed models (GLMMs) to attempt to account for variation in responses caused by random factors such as block or irrigation coverage. GLMMs were initially implemented with the R package *lme4* using the functions *lmer* for continuous response variables and *glmer* for the rest (Bolker *et al.* 2009, Bates *et al.* 2015). Tree species were analyzed separately. Models contained the herbicide (H0, H1, H2, H3) and adjuvant treatments (A0, A1, A2) as fixed factors, and their two-way interaction. Response variables were survival, height increment and root collar diameter increment after 1 or 2 years. Where data were not normally distributed, or heteroscedastic, or contained outliers, different error distributions, link functions and/or transformations were applied to improve model fit. R^2 values were produced to show the proportion of variation in the response variable explained by the model, and the importance of the experimental treatment variables were measured with log likelihood ratio tests (Bolker *et al.* 2009, Thomas *et al.* 2015).

After assessing the overall treatment significance, *post hoc* comparisons between groups were carried out using the R package *emmeans* (Lenth 2024). *P*-values produced from contrasts were adjusted for multiple comparisons; the Sidak method was used for contrasts between the untreated control (H0A0) and individual treatments, and the more conservative Tukey method was used for multiple comparisons (pairwise contrasts) between all treatments (Lenth 2024). Throughout this paper, any results referred to as "significant" are so at the $P \leq 0.05$ level. Back transformed marginal means were calculated using emmeans and plotted along with 95% confidence intervals, and annotated with letters representing the outcome of the Tukey multiple comparison tests, with asterisks for significant differences resulting from the Sidak multiple comparison tests (Lenth 2024). Means that had been back transformed from the GLMM estimates were plotted, rather than the raw data, because the former were the values used in the significance testing and take account of random effects such as differences between blocks and irrigation.

For reason of brevity, only plots of those species with treatments showing significantly lower survival or height increment compared to the untreated controls are included in the results section. Similar plots for root collar diameter increment are available in the *Supplemental Data*. Also see the *Supplemental Data* for a more detailed description of the statistical analysis undertaken, which includes the packages and functions used, the final GLMM structures including fixed and random effects, and the rationale behind the analytical choices made.

Reduction in tree/shrub survival caused by each treatment, compared to the untreated control, using the back transformed means at the two assessment dates, was calculated. Increment and survival were considered on a season-by-season basis, i.e. the figures for 15 months after treatment represent the changes in survival and height increment for the second growing season only. An indicative "susceptibility/crop tolerance rating" was then assigned, following the terminology used on UK plant protection product labels (i.e. susceptible; moderately susceptible;

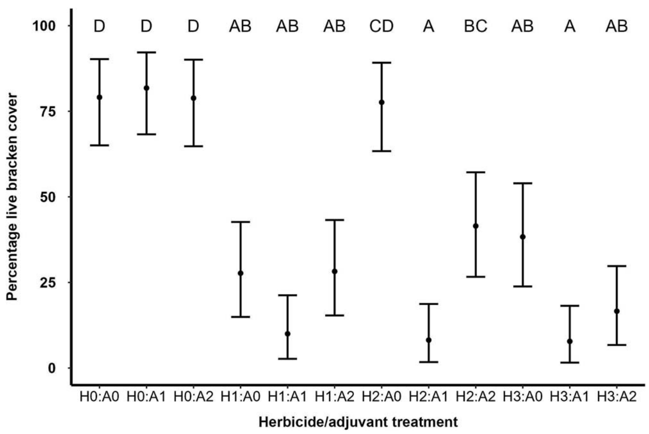

Figure 1. Percentage live cover of bracken by herbicide/adjuvant treatment at Yateley Heath, experiment 1, July 2019, 11 months after spraying. *Notes:* The black data points show back transformed, estimated marginal means, with the error bars representing the 95% confidence intervals of these estimates. The superscript lettering shows significant differences between pairwise contrasts of arcsine transformed, estimated marginal means, by herbicide/adjuvant treatment at the $P \leq 0.05$ threshold, with values adjusted for multiple comparisons through Tukey's method. Treatments not sharing the same letter (A–D) are significantly different ($P \leq 0.05$). See Table 3 for full details of the experimental treatments, including treatment codes.

moderately resistant; resistant) (HSE 2020), but utilizing a considerably more conservative scale to derive the ratings than those used earlier for weed susceptibility. See Table 6 for further details.

Results

Experiment 1—Efficacy

Overall, herbicides significantly reduced live bracken cover compared to the untreated controls, but the magnitude of the effect depended on the herbicide and adjuvant used (Fig. 1). Asulam (H1) significantly reduced live bracken cover by at least 65%, but there was no significant difference between adjuvant treatments (H1 A0, H1 A1, H1 A2). In other words, the adjuvants Mixture B NF® and Toil® did not improve the efficacy of asulam.

Amidosulfuron (H2, H3) also significantly reduced live bracken cover, but the effect varied depending on which rate and adjuvants were used. At a rate of 0.045 kg a.i. ha^{-1} amidosulfuron (H3A0), live bracken cover was reduced by approximately half, which was not significantly different from the levels of control provided by asulam. At this application rate, the use of adjuvants (A1, A2) provided no significant improvement in bracken control, although there was an apparent increase in efficacy from adding Mixture B NF® which was only marginally non-significant (H3A1 v H3A0; $P = 0.06$). By contrast, at the lower rate of 0.023 kg a.i. ha^{-1} amidosulfuron (H2A0), the resulting live bracken cover was not significantly different from the untreated plots (H0). In other words, 0.023 kg a.i. ha^{-1} amidosulfuron used without adjuvants was ineffective in controlling bracken. However, when Mixture B NF® was added (H2A1) efficacy was improved dramatically, with bracken cover being reduced by ~90% compared to the untreated plots (H0), a level of control that was not significantly different from that given by asulam (H1) or the higher application rate of amidosulfuron (H3). The adjuvant Toil® (H2A2) also significantly improved efficacy compared to the untreated plots (H0), but it was not as effective in doing this as Mixture B NF® (H2A1).

Finally, there were no significant differences between the untreated (water only, no herbicide) plots (H0 A0, H0 A1, H0 A2) indicating, as expected, that the adjuvants Mixture B NF® and Toil® by themselves had no effect on bracken cover.

Indicative susceptibly of bracken to the various treatments, using the categories "susceptible", "moderately susceptible", "moderately resistant", or "resistant" is given in Table 5.

Experiment 2—Tree and shrub tolerance

The effects of the herbicide/adjuvant treatments varied between species, but in general there were few significant, consistently negative impacts on survival or growth compared to the untreated control, and even where reductions did occur the magnitude of the effects were usually very small.

Asulam (H1) had no effect on tree or shrub survival in the first year after treatment, but during the second year there were significant reductions in survival in Tingiringi gum (*Eucalyptus glaucescens* Maiden and Blakely) when no adjuvant was used (H1A0; ~30% reduction compared to the untreated control) or when Mixture B NF® was added (H1A1; ~50% reduction). Asulam plus Mixture B NF® (H1A1) was also associated with significantly reduced survival in Wellingtonia [*Sequoiadendron giganteum* (Lindl.) J. Buchh.] by ~30%, and Asulam plus Toil® significantly reduced survival in birch (*Betula pendula* Roth) by ~50% (Fig. 2).

The only significant effect on growth in the season after spraying was for Tingiringi gum, where height increment was reduced by ~15 cm compared to the untreated control by the Asulam plus Mixture B NF® (H1A1) treatment (Fig. 3). In the second year after treatment, Asulam with no adjuvant (H1A0) resulted in significantly reduced height growth compared to the untreated control in Wellingtonia (4 cm less) and western hemlock [*Tsuga heterophylla* (Raf.) Sarg.] (3 cm less) (Fig. 4). Asulam plus Mixture B NF (H1A1) significantly reduced height increment in Maritime pine (*Pinus pinaster* Aiton) (by 20 cm) and western hemlock (by 3 cm), and diameter increment in Wellingtonia (by 1 mm), Scots pine (by 1 mm), and Maritime pine (by 3 mm). Asulam plus Toil® (H1A2) resulted in similarly significant but only small reductions in height and diameter increment in Wellingtonia (Fig. 4 and Fig. S2).

Amidosulfuron (H2, H3) had no significant effect on any tree or shrub species in the first season after treatment, save for a small (<1 mm) reduction in root collar diameter increment of sycamore (*Acer pseudoplatanus* L.) following the 0.045 kg a.i. amidosulfuron ha^{-1} plus Mixture B NF® (H3A1) treatment (Fig. S1).

By the end of the second season after treatment the only significant effect on survival was a 20% reduction in the 0.045 kg a.i. ha^{-1} amidosulfuron plus Mixture B NF® treatment (H3A1) for western hemlock (Fig. 2). Height increment of oak (*Quercus robur* L.) was significantly reduced by 18 cm in the 0.023 kg a.i. ha^{-1} amidosulfuron with no adjuvant (H2A0) treatment, and when Mixture B NF® (H2A1) was used the height increments of Maritime pine and Wellingtonia were reduced by 9 cm and 3 cm, respectively, and height and diameter increments of Leyland cypress (*Cupressus x leylandii* A. B. Jacks. and Dallim.) were also reduced (by 15 cm and 2 mm) (Fig. 4 and Fig. S2). However, in all of these cases the higher dose rate of amidosulfuron (H3), that logically ought to be more damaging, had no significant effect.

At the higher rate of 0.045 kg a.i. ha^{-1} amidosulfuron (H3A0), second year height growth increment of Tingiringi gum and Wellingtonia was significantly reduced by 7 cm and 3 cm respectively, and when Mixture B NF® (H3A1) or Toil® (H3A2) was used the height increments of noble fir (*Abies procera* Rehder) and Tingiringi gum were reduced by ~3 cm and 24 cm, respectively (Fig. 4).

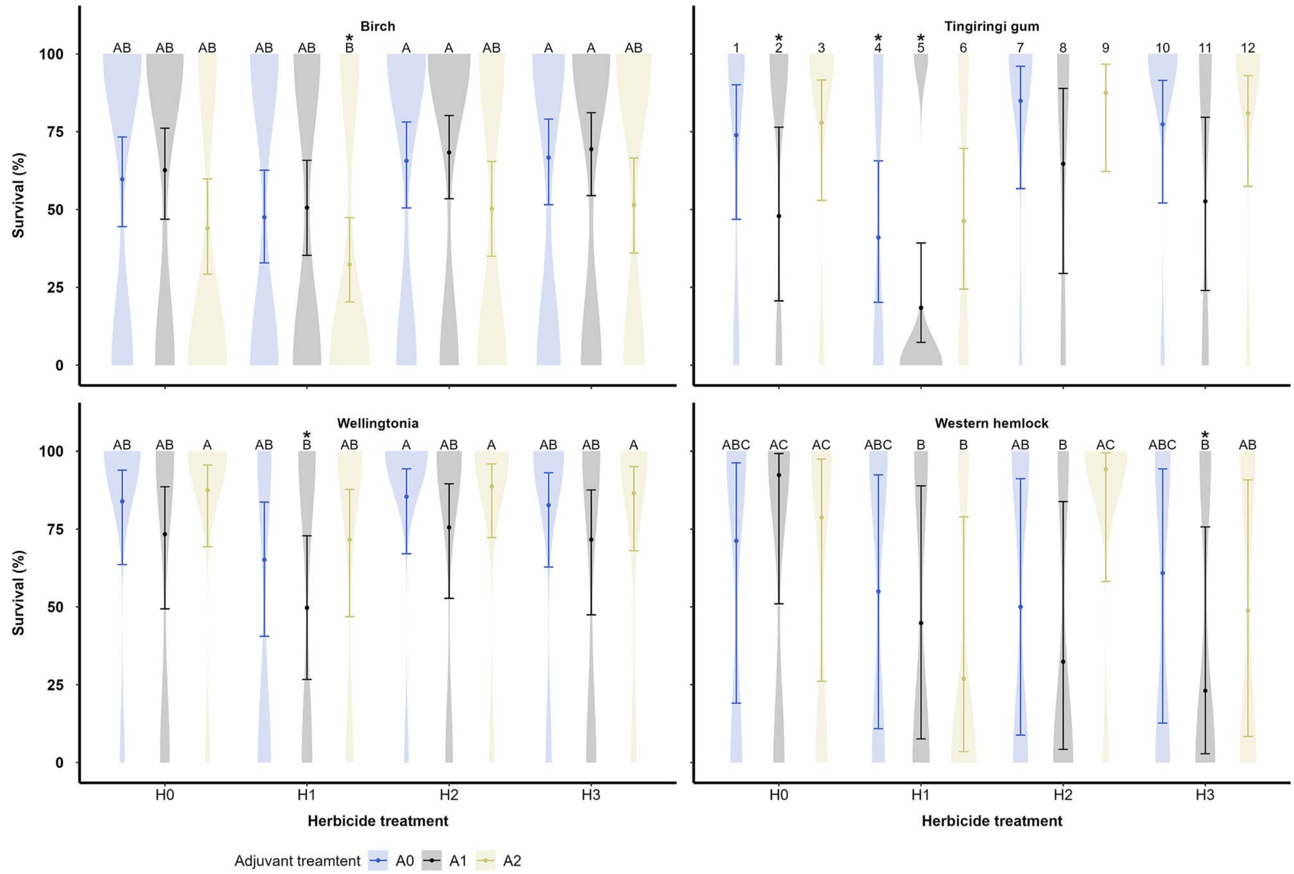

Figure 2. Second year survival of birch, Tingiringi gum, Wellingtonia, and western hemlock by herbicide/adjuvant treatment at Headley Research Enclosure, experiment 2, October 2022, 15 months after spraying. *Notes:* The large dots show back-transformed estimated marginal means from the generalized linear mixed models, with the error bars representing the 95% confidence intervals of these estimates. The "violin" plots show the frequency of the raw data points associated with each estimated mean, where the violin's width at a y-value is proportional to the point density nearby. The superscript lettering shows significant differences between the estimated marginal means following the multiple comparison test (Tukey). Treatments not sharing the same letter (A–D) are significantly different ($P \leq 0.05$). Treatments annotated with a "*" are significantly different ($P \leq 0.05$) from the untreated control (H0A0), tested using the Sidak method. On Tingiringi gum for clarity of presentation numbers have replaced letters to signify different groups:- 1 = ADEFGHIJK; 2 = ABEFGHIJK; 3 = ABDGHIJK; 4 = BCDEFGHIJK; 5 = CDEFGHIJK; 6 = ABEFHIJ; 7 = ADEFGHIJKL; 8 = ABDEGHJKL; 9 = L; 10 = ABDEGIJKL; 11 = ABDEFHIJ; 12 = ABDEFGHIKL. As there was no survival variation in the raw data for H2A2 (100 ± 0%), in this case significant differences were identified by conservative one-sample Wilcoxon rank testing of each of the other treatments against a value of 100% (Wilcoxon 1945, Heinze and Schemper 2002). See Table 3 for full details of the experimental treatments, including treatment codes.

As expected, the adjuvants by themselves caused few significant effects. Mixture B NF® (H0A1) resulted in a significant reduction in first year root collar diameter increment in sycamore of 0.6 mm, in second year root collar diameter in Leyland cypress of 14 mm, and in second year height increment in noble fir of 2 cm. Toil® (H0A2) resulted in a 4 cm reduction in second year height increment in wellingtonia (Fig. 4; Figs S1 and S2).

In general, there were few significant differences between the treatments themselves, evident from the more conservative pairwise multiple comparison test. There was only one instance of what we found to be the most effective bracken killing treatment in Experiment 1, amidosulfuron plus Mixture B NF®, appearing to be more damaging than the current active control asulam (H1A0). This was for second year height growth increment of noble fir, which was significantly lower in the 0.045 kg a.i. ha^{-1} treatment (H3A1) than asulam (H1A0) (Fig. 4).

Conversely, second year survival of Tingiringi gum in the active control (H1A0) treatment was significantly lower than when amidosulfuron was applied at either rate without adjuvants (H2A0; H3A0) (Fig. 2).

There were no examples of the higher rate of amidosulfuron (H3A0) being more damaging than the half rate amidosulfuron treatment with Mixture B NF® (H2A1).

Indicative crop tolerance of the tree/shrub species to the various treatments, using the categories "susceptible", "moderately susceptible", "moderately resistant", or "resistant" is given in Table 6.

Discussion

We found that 0.045 kg a.i. ha^{-1} amidosulfuron was as effective as asulam in controlling bracken. Based on the efficacy categories given in Table 5, bracken could be conservatively described as ranging from "moderately susceptible" to "moderately resistant" to both herbicides. Large scale efficacy trials involving aerial and ground based sprays in moorland have also reported good levels of control using amidosulfuron (Brown 2022, 2023). However, when applied without adjuvants, we found that the half rate treatment (0.023 kg a.i. ha^{-1} amidosulfuron), known to give better tree tolerance (Stokes and Willoughby 2007), was ineffective.

In our work we found no benefit from using adjuvants with asulam, but they did improve the efficacy of amidosulfuron. When Mixture B NF® was used, dose rates could be reduced by half (to 0.023 kg a.i. ha^{-1} amidosulfuron) with no loss of efficacy. Following the categories given in Table 5, bracken could be described as being at least 'moderately susceptible' to this reduced rate

Table 6. Indicative crop tolerance, 3 and 15 months after spraying with asulam or amidosulfuron, for 21 tree and shrub species.

Experimental treatment	Coast redwood		Heather		Douglas fir		Oak		Beech		Grand fir		Japanese red cedar	
	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying
H0 A1: water plus Mixture B NF®														
H0 A2: water plus Toil®														
H1 A0: 4.0 kg a.i. ha^{-1} asulam, no adjuvant														
H1 A1: 4.0 kg a.i. ha^{-1} asulam, plus Mixture B NF®														
H1 A2: 4.0 kg a.i. ha^{-1} asulam, plus Toil®														
H2 A0: 0.023 kg a.i. ha^{-1} amidosulfuron, no adjuvant								*H						
H2 A1: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®														
H2 A2: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Toil®														
H3 A0: 0.045 kg a.i. ha^{-1} amidosulfuron, no adjuvant														
H3 A1: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®														
H3 A2: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Toil®														

Experimental treatment	Leyland cypress		Macedonian pine		Maritime pine		Noble fir		Norway spruce		Scots pine		Silver birch	
	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying
H0 A1: water plus Mixture B NF®		*D						*H						
H0 A2: water plus Toil®														
H1 A0: 4.0 kg a.i. ha^{-1} asulam, no adjuvant														
H1 A1: 4.0 kg a.i. ha^{-1} asulam, plus Mixture B NF®						*HD						*D		
H1 A2: 4.0 kg a.i. ha^{-1} asulam, plus Toil®												*D		*S
H2 A0: 0.023 kg a.i. ha^{-1} amidosulfuron, no adjuvant														
H2 A1: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®		*HD				*H								
H2 A2: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Toil®														
H3 A0: 0.045 kg a.i. ha^{-1} amidosulfuron, no adjuvant														
H3 A1: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®								*H						
H3 A2: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Toil®								*H						

Experimental treatment	Sitka spruce		Cherry		Sycamore		Tingiringi gum		Wellingtonia		Western hemlock		Western red cedar	
	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying	Susceptibility 3 months after spraying	Susceptibility 15 months after spraying
H0 A1: water plus Mixture B NF®					*D									
H0 A2: water plus Toil®										*H				
H1 A0: 4.0 kg a.i. ha^{-1} asulam, no adjuvant								*S		*H		*H		
H1 A1: 4.0 kg a.i. ha^{-1} asulam, plus Mixture B NF®							*H	*S		*SD		*H		
H1 A2: 4.0 kg a.i. ha^{-1} asulam, plus Toil®										*HD				
H2 A0: 0.023 kg a.i. ha^{-1} amidosulfuron, no adjuvant														
H2 A1: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®										*H				
H2 A2: 0.023 kg a.i. ha^{-1} amidosulfuron, plus Toil®														
H3 A0: 0.045 kg a.i. ha^{-1} amidosulfuron, no adjuvant								*H		*H				
H3 A1: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Mixture B NF®					*D			*H				*S		
H3 A2: 0.045 kg a.i. ha^{-1} amidosulfuron, plus Toil®								*H						

Notes: See Table 3 for full details of the experimental treatments, including treatment codes. Reduction in survival caused by each treatment was calculated for each species at each date after treatment as follows:- Percentage reduction in survival = [(survival untreated control—survival herbicide treatment)/survival untreated control]∗100. Reduction in height increment was calculated as follows:- Percentage reduction in height increment = [(height increment untreated control—height increment herbicide treatment)/height increment untreated control]∗100. The color code used to indicate susceptibility based on these calculated reductions in survival or growth is as follows:-

= Resistant. Compared to the untreated control H0A0, ≤5% reduction in survival and ≤ 10% reduction in height growth increment.

= Moderately Resistant. Compared to the untreated control H0A0, ≤10% reduction in survival and 11%–25% reduction in height growth increment.

= Moderately Susceptible. Compared to the untreated control H0A0, ≤10% reduction in survival and > 25% reduction in height growth increment.

= Susceptible. Compared to the untreated control H0A0, >10% reduction in survival. *S = Significantly ($P \leq 0.05$) lower survival than the untreated control H0A0. *H = Significantly ($P \leq 0.05$) lower height growth increment than the untreated control H0A0. *D = Significantly ($P \leq 0.05$) lower root collar diameter growth increment than the untreated control H0A0.

amidosulfuron plus Mixture B NF® adjuvant combination, and crucially it appeared to be just as effective in controlling bracken as using asulam. Using Toil® adjuvant gave similar results, although benefits were not as great as for Mixture B NF®. This opens up the possibility that a lower dose rate of amidosulfuron than previously thought, with potentially less impact on crops and other non-target vegetation, might be a viable alternative to the use of asulam for controlling bracken.

Our efficacy treatments were carried out in mid-August 2018, which was selected as being during the optimum period to apply asulam on the sites in question in the south of England, as recommended on the product label (UPL 2021), when bracken fronds had fully unfurled but were showing no signs of senescence. West et al. (1995) also reported good results from applying amidosulfuron in late July/early August. However, as amidosulfuron is also taken up by roots (MacBean 2012), earlier applications (late June to early July), before bracken fonds have fully unfurled, might be equally or more effective, although in this scenario tree tolerance may be worse, and impacts on non-target vegetation greater, due to more of the spray being deposited on them.

Some tree species appeared to be more susceptible than others, but in general there were few statistically significant, negative impacts on survival or growth. Where reductions did occur they were usually relatively small, and in practical terms were likely to have been less than would have occurred if the same species had been left to fend for itself in an uncontrolled, dense bracken infestation. Although there were apparently more numerous examples of reductions in survival or growth in the second growing season compared to the first, this may be due in part to localized failure of irrigation leading to drought conditions being experienced in some plots and species, rather than purely delayed phytotoxic effects of the herbicide applications themselves. In addition, in

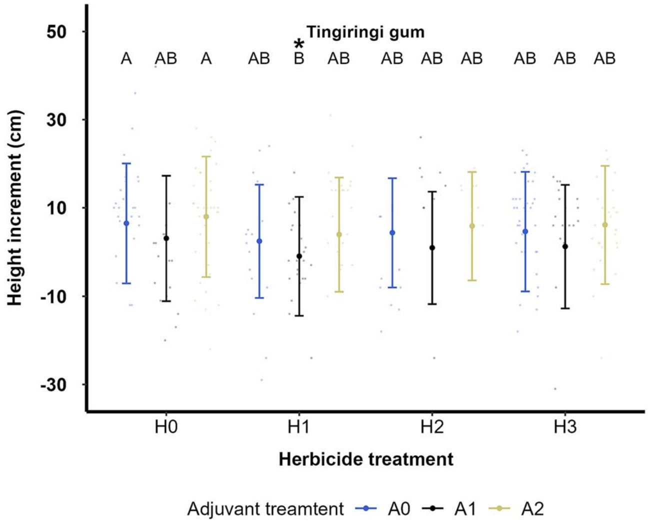

Figure 3. First year height growth increment of Tingiringi gum by herbicide/adjuvant treatment at Headley Research Enclosure, experiment 2, October 2021, 3 months after spraying. *Notes:* The large dots show back transformed estimated marginal means from the generalized linear mixed models, with the error bars representing the 95% confidence intervals of these estimates. Raw data points associated with each estimated mean are shown as lighter, smaller dots. The superscript lettering shows significant differences between the estimated marginal means following the multiple comparison test (Tukey). Treatments not sharing the same letter (A–B) are significantly different ($P \leq 0.05$). Treatments annotated with a "*" are significantly different ($P \leq 0.05$) from the untreated control (H0A0), tested using the Sidak method. See Table 3 for full details of the experimental treatments, including treatment codes.

many cases the apparent reductions occurred as a result of lower, but not higher dose rates, and there were also several examples of apparently significant increases in growth caused by the herbicide/adjuvant treatments (see *Supplemental Data*). Overall then, although we did record some negative effects associated with the different herbicide and adjuvant treatments, there is no clear, consistent evidence of unacceptable levels of phytotoxicity.

Previous studies have indicated that amidosulfuron appears to be better tolerated than the other sulfonylureas (Dixon *et al.* 2006), with Stokes and Willoughby (2007) reporting that Corsican pine (*Pinus nigra ssp. laricio* Maire), Douglas fir [*P. menziesii* (Mirb.) Franco], Japanese larch [*Larix kaempferi* (Lamb.) Carr.], lodgepole pine (*Pinus contorta* Douglas ex Loudon), noble fir, Norway spruce [*Picea abies* (L.) H. Karst.], Scots pine (*Pinus sylvestris* L.), Sitka spruce [*Picea sitchensis* (Bong.) Carr.], ash (*Fraxinus excelsior* L.), beech (*Fagus sylvatica* L.), birch, oak, and willow (*Salix* sp.) were all moderately or completely resistant when sprayed with 0.03 kg a.i. ha^{-1} amidosulfuron in active growth in July, but alder [*Alnus glutinosa* (L.) Gaertn.], cherry (*Prunus avium* L.), Norway maple (*Acer platanoides* L.), poplar (*Populus* sp.), sycamore, Sweet chestnut (*Castanea sativa* Mill.) and western red cedar (*Thuja plicata* Donn) were more severely damaged. At 0.06 kg a.i. ha^{-1} amidosulfuron only oak, willow, Douglas fir, Japanese larch, lodgepole pine, Norway spruce and Scots pine appeared moderately tolerant.

In our work, 0.023 kg a.i. ha^{-1} amidosulfuron plus Mixture B NF®, which was as effective as asulam in controlling bracken, was generally as well tolerated by most tree and shrub species, including sycamore and western red cedar. The most vulnerable species appeared to be Leyland cypress, noble fir, Maritime pine, Wellingtonia and western hemlock, although it is worth noting that in these latter three cases asulam appeared to be equally damaging.

The higher rate of amidosulfuron did not consistently cause more damage to crop species in our work, and similarly using a lower rate of amidosulfuron plus Mixture B NF® did not improve crop safety. However, given that a similar levels of bracken control can be achieved, by using a lower amount of active ingredient if Mixture B NF® adjuvant is used, this would logically appear to be the preferable approach, as it may help to improve crop tolerance in operational practice, and fits with the aims of government policy (Forest Research 2023) and voluntary certification schemes (UKWAS 2018) to reduce the amount of herbicide applied where possible.

Using the conservative categories for crop tolerance given in Table 6, coast redwood [*Sequoia sempervirens* (D. Don) Endl.], Douglas fir, grand fir (*Abies grandis* Lindl.), Japanese red cedar [*Cryptomeria japonica* (L.f.) D. Don], Macedonian pine (*Pinus peuce* Griseb.), Norway spruce, oak, Scots pine, birch, Sitka spruce, cherry, sycamore and western red cedar, could be considered likely to be resistant or moderately resistant to 0.023 kg a.i. ha^{-1} amidosulfuron plus Mixture B NF®. We can be reasonably confident that these species will not suffer significant death or growth suppression if 0.023 kg a.i. ha^{-1} amidosulfuron plus Mixture B NF® is used instead of asulam to control bracken, particularly given that in many cases trees are likely to be growing under a continuous canopy of fronds when spraying takes place. For these tree species, the risk of leaving a dense infestation of bracken uncontrolled around trees is likely to be greater than spraying with amidosulfuron. Initial indications from our work are that heather, Leyland cypress, Maritime pine, noble fir, Tingiringi gum, Wellingtonia, and western hemlock may be somewhat more vulnerable, and further work is required to confirm their crop tolerance. In all cases more research is required to confirm crop tolerance, and small scale user trials are recommended to test safety in local conditions before embarking on any large scale treatment.

In contrast to the positive findings described in this paper, a series of large scale trials undertaken by Professor Roy Brown between 2012 and 2024 in conjunction with the Bracken Control Group, who also funded the final stages of the work, concluded that amidosulfuron was not suitable for use in bracken control on open grassland. This was because although efficacy was promising, there were concerns over persistence in the soil as in some trials activity was recorded four or more years after application. While it was thought this could be an advantage in some situations, it could also prevent the establishment of a more diverse ground flora after bracken removal. It was suggested that because the main uptake of amidosulfuron is via soil rhizomes, for maximum efficacy application would need to take place relatively early in the growing season (early July) to ensure spray is not significantly intercepted by fronds, and this is likely to result in a higher impact on non-target species such as soil invertebrates, and disturbance to ground nesting birds. In addition, as root hairs on the rhizomes are killed by the application, follow up treatments to control surviving bracken plants are likely to be less effective than would have been the case with asulam (Brown 2022, 2023).

However, in our work late (mid-August) sprays of amidosulfuron plus adjuvant to a continuous canopy of bracken fronds were found to be just as effective as applying asulam, albeit using relatively high volume rates, and the separate crop tolerance study found little impact on trees from applications made earlier on in the season (mid-July). In addition, in a forestry context the aim is normally only to kill sufficient bracken plants to

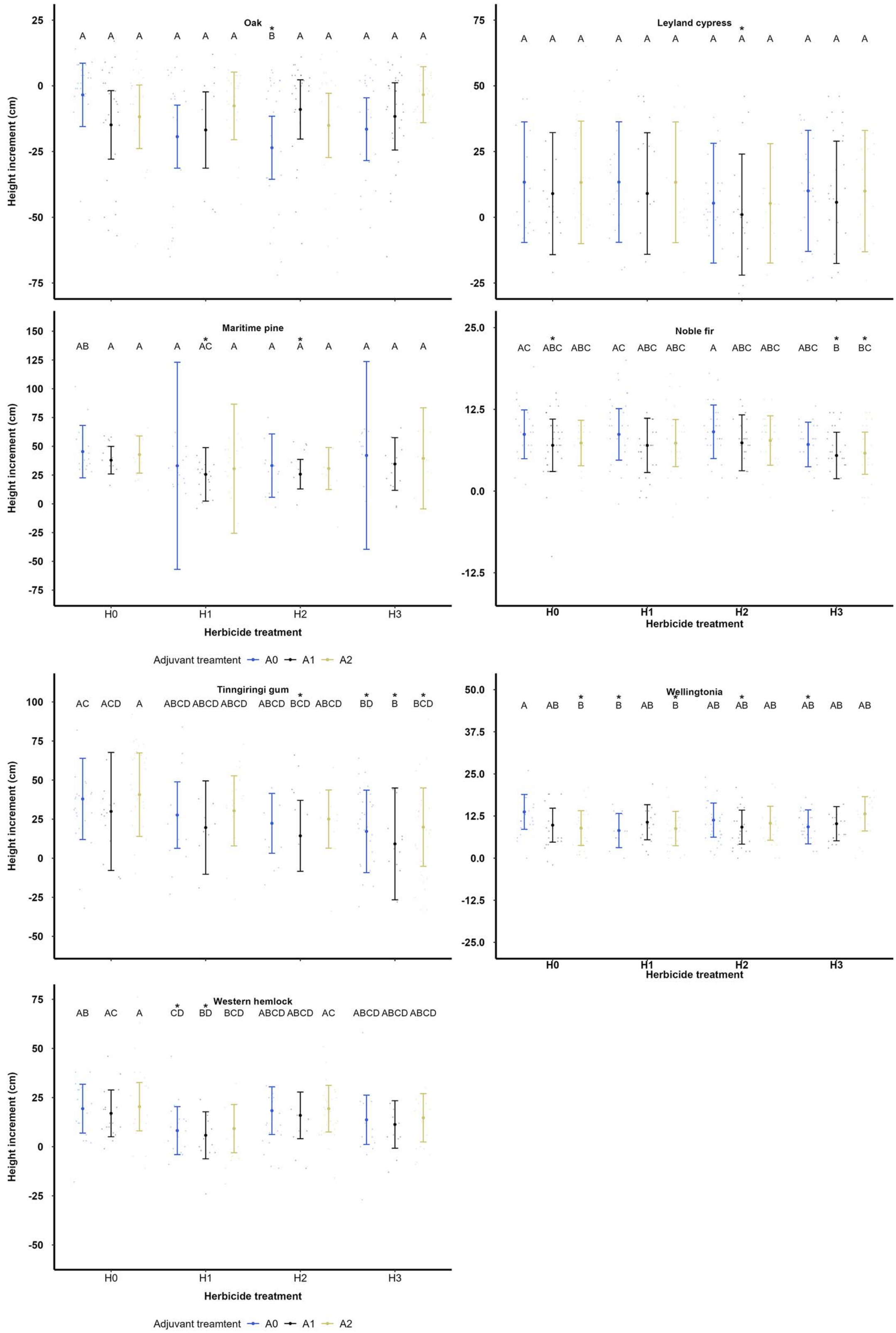

Figure 4. Second year height growth increment of oak, Leyland cypress, maritime pine, noble fir, Tingiringi gum, wellingtonia, and western hemlock by herbicide/adjuvant treatment at Headley research enclosure, experiment 2, October 2022, 15 months after spraying. *Notes:* The large dots show back transformed estimated marginal means from the generalized linear mixed models, with the error bars representing the 95% confidence intervals of these estimates. Raw data points associated with each estimated mean are shown as lighter, smaller dots. The superscript lettering shows significant differences between the estimated marginal means following the multiple comparison test (Tukey). Treatments not sharing the same letter (A–D) are significantly different ($P \leq 0.05$). Treatments annotated with a "∗" are significantly different ($P \leq 0.05$) from the untreated control (H0A0), tested using the Sidak method. See Table 3 for full details of the experimental treatments, including treatment codes.

allow young trees to establish. Total eradication of the bracken is not required, and hence follow up treatment to control plants that survived earlier applications is rarely undertaken. Further research is nevertheless required into the use of earlier application dates, as this might prove to be even more effective in killing bracken, albeit with the likelihood of reduced spray interception by fronds, and hence a potentially greater risk to trees and other non-target plant species, and soil invertebrates. As the relatively high volume rates used in our work may not be practical in many situations, research should also be undertaken into the efficacy of later applications at lower volume rates. However, one caveat to note when considering further research is that currently amidosulfuron is not approved for use in forestry situations, and there is some uncertainty over the future availability of any amidosulfuron products in the UK beyond 2028.

Conclusions

Our work suggests that amidosulfuron can be equally or more effective than asulam in controlling competing bracken in a forestry context, and is in many cases is likely to be no more damaging to young trees.

Therefore although further research is required to confirm crop tolerance, where there is no viable non-chemical option and crop trees might otherwise die, 0.023 kg a.i. ha^{-1} amidosulfuron [e.g. as 0.03 kg ha^{-1} Squire Ultra® (75% w/w amidosulfuron)] plus Mixture B NF® adjuvant at 2% of final spray volume, may be a potentially suitable replacement for the use of asulam to control bracken in recently planted stands of coast redwood, Douglas fir, grand fir, Japanese red cedar, Macedonian pine, Norway spruce, oak, Scots pine, silver birch, Sitka spruce, cherry, sycamore, and western red cedar. However, it is strongly recommended that small scale user trials are undertaken to test crop safety in local conditions before embarking on any large scale treatment.

Currently amidosulfuron is not approved for use in forestry situations, and there is some uncertainty over the future availability of any amidosulfuron products in the UK beyond 2028.

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Author contributions

Ian H. Willoughby (Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Writing—original draft, Writing—review & editing), Toni Clarke (Formal analysis), and Kris Sales (Formal analysis).

Supplementary data

Supplementary data are available at *Forestry* online.

Conflict of interest: None declared.

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Data availability

All relevant data are given in the text and its online supplementary material. The data underlying this article will be shared on reasonable request to the corresponding author.

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