Monitoring of bracken control methods and their impact on the historic environment

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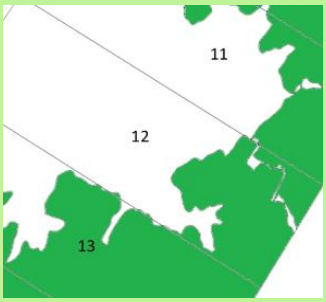

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Executive summary

Bracken (*Pteridium aquilinum*) has been identified as the primary threat to the integrity of many scheduled monuments in the north and south-west of England. Bracken also has a major impact on the visibility of archaeology in these regions, affecting public enjoyment and academic study of archaeological sites. This report presents the findings of a four-year project funded by Historic England to study the efficacy of a number of bracken control techniques and their impact on the historic environment. The study comprised field-based trials at three sites in England using a number of mechanical and chemical control methods and observed their effects on the bracken, understorey vegetation and proxy archaeological remains.

A previous iteration of this project (funded by Natural England, 2011-2014) started to look at the impact of bracken control methods on the historic environment at one of the sites that forms part of this study; Ingram Farm, Northumberland. The research, set in large plots on the open hill, used grids of part-buried stones as a proxy for archaeological remains. The bracken around the grids was then subjected to different mechanical control methods; cutting, bashing and intense stocking with cattle and sheep. The results to 2014 suggested that mechanical treatments assist the control of bracken with least impact on the historic environment, whereas intense cattle stocking was damaging to the ground and caused displacement of the stones in the grids. However, more evidence was required so that Historic England can provide its stakeholders with robust advice and guidance about effective, economically viable and environmentally acceptable techniques for bracken control.

This phase of the research has built on the previous work and expanded it to additional sites; one at Fawdon Farm in Northumberland and the other at Challacombe Farm, Devon.

Part-buried, painted cast concrete cylinders were used as proxy archaeological remains at all three sites. Damage and displacement of the cylinders was recorded through the course of the project to assess how bracken control methods have caused or prevented harm to the historic environment The project continued to examine changes in vegetation resulting from mechanical bracken control methods; cutting, bashing and trampling resulting from winter cattle foddering. It also included a new mechanical treatment; 'double-bashing'; bashing the bracken twice within a year, a liming treatment plus four different herbicide treatments.

Vegetation dynamics in response to bracken control treatments

There was a significant reduction in the different measures of bracken vigour in most herbicide and all mechanical treatments. Reduced bracken vigour was also observed on the plots receiving winter cattle foddering.

In the Cut and Bashed treatments there was greater species diversity and understorey cover than the Control by the end of the project. The plots that had been *cut* since 2011 had the lowest bracken vigour scores compared with the corresponding Bash treatment and Controls. These Cut plots contained large tracts which were either bracken-free or contained a very low density of bracken. By the end of the project there was also significantly greater species diversity and understorey cover in the 2016-established plots receiving mechanical treatments, compared with the Controls.

The plots at Fawdon and Challacombe farms had a high cover of bluebells (*Hyacinthoides non-scripta)* in spring, which was not captured by the vegetation survey. It was *visually* clear during other fieldwork carried out in spring, that the mechanical and chemical treatments had a considerable negative impact on the bluebells.

Damage to the historic environment and proxy archaeological remains

Analysis of movement and damage to the proxy archaeological remains showed little or no effects in the Control and chemical treatments. Some damage and displacement *was* observed in those treatments, possibly attributable to livestock and farm traffic. It is also possible that this displacement, like in some of the other treatments, could have been caused by the cylinders settling into their excavated holes.

In contrast, there *has* been damage and displacement of cylinders in the plots undergoing mechanical or cattle foddering treatments. By the end of the project there was significantly more disturbed ground caused by cattle poaching associated with winter foddering in those plots. Trampling by cattle also caused significant cylinder displacement, but not damage. Displacement of the proxy remains was most marked in the Cut and Double-bashed treatment plots, more so at Challacombe Farm, Devon. Cutting and bashing/double-bashing often caused substantial concrete cylinder displacement *and* damage.

However, the extent of cylinder displacement and damage observed in the Cut treatment suggests that cutting can lead to either a high level of displacement and damage to a cylinder or, through the establishment of a tight grass sward, results in the cylinder being protected and even partially covered by the developing sward. In some instances, both occurred, with cylinders displaced and damaged early in the experiment, then bedding into their new locations surrounded by dense grass.

The patterns of displacement and damage to the concrete cylinders, particularly the differences between sites and plots suggests that the effects of mechanical bracken control methods on the concrete cylinders are to some extent determined by the interplay of microtopography, equipment settings and the way in which any given individual uses the equipment for mechanical control of bracken.

Evaluation of Unmanned Aerial Vehicle-based data capture for bracken mapping and assessment of damage to the historic environment, plus ground-based GPS mapping of bracken cover

This project also included assessments of remote data capture by Unmanned Aerial Vehicles (UAVs) for measuring bracken extent/vigour and ground displacement. The UAV-based assessment of bracken cover was carried out alongside a ground-based mapping exercise using GPS in order to assess the efficacy of each for measuring bracken extent in response to bracken control.

The bracken was GPS-mapped from the ground by attempting to record all areas with 100% cover of bracken. The GPS-based bracken mapping was therefore unable to capture the full extent of bracken, but was a fair means of capturing the relative extent of full cover bracken between treatment plots. It was a poor way of investigating changes in the ‘fronts’ of bracken stands.

For the UAV bracken mapping, images of the vegetation were captured by UAV in the red and green spectral bands. These were converted to maps of normalised difference vegetation index (NDVI) scores. It was intended to use these to determine a 'signature' range of NDVI scores for bracken cover. There *was* a positive correlation between the NDVI data and ground-measured bracken cover, suggesting that bracken *can* be identified in a narrow range of NDVI scores. However, these NDVI score ranges were site-specific. It is not known whether this was due to *actual* site-specific differences in the vegetation or whether these were an artefact of the data capture technique. For this to be a viable technique for assessing bracken cover, ground-truthing per flight or site is recommended.

The UAV-based measurement of *ground displacement* was carried out to investigate whether the technique would be viable for assessing damage to the historic environment arising from bracken control. Again, the frequency distribution of the UAV data was site-specific. There *were* positive correlations between the UAV-measures of displacement and ground-based measures of disturbance and displacement, but these are likely to have been coincidental. Rather than recording actual ground height changes, the UAV data-capture may have recorded the likes of bracken litter depth changes, which are associated with the *vegetation* composition changes arising from bracken control. As it stands, much of the data appears to be meaningless, and more work would be required to assess the efficacy of the technique or refine it in conjunction with ground-truthing.

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1. INTRODUCTION, AIMS AND OBJECTIVES

The growth of bracken rhizomes can have a serious impact on the integrity of archaeological remains through their physical displacement of those remains. Stands of living bracken and bracken *litter* are also deleterious to the historic environment; impacting the visibility of archaeological remains. In tandem with damage caused by rhizomes, loss of visibility affects the academic study of archaeological sites. This loss of visibility also impacts public enjoyment of such sites. Consequently, bracken is considered to be the primary threat to the integrity of many scheduled monuments in the north and south-west of England.

In order to understand how bracken control techniques can assist with the preservation of historical sites, a research study funded by Natural England was undertaken between 2011 and 2014 at Ingram Farm, Northumberland (see Scott *et al*, 2014). This study tested the effectiveness of different bracken control methods on bracken and the understorey. The effects of those bracken control methods on the historic environment were also investigated, by measuring changes in cover of disturbed ground and displacement of proxy archaeological remains (cobble-sized stones part-buried in the ground).

The findings of that phase of the research showed promising indications about the effectiveness of different bracken control methods and how they might affect the historic environment. However, it was felt that the project duration was insufficient to determine if there had been a long-term ecological response. Furthermore, the experiment to look at displacement of proxy archaeological remains required additional study to better understand the responses between treatments. In order to address these matters, this research was commissioned in 2016 by Historic England with the aim of building on the existing data and broadening the evidence base. The primary objectives of this project are to produce robust and targeted research which will enable Historic England and partner organisations to provide better advice and guidance on how best to control bracken on archaeological sites with minimal impact on the archaeological remains of those sites.

This project ran from 2016-2020, continuing to collect data from a number of the existing plots at Ingram Farm, Northumberland, and expanding to two other farms; one in Northumberland and the other in Devon. A number of additional treatments were introduced in this project, including chemical control of bracken. The methodology for measuring effects of bracken control on the historic environment has also been broadened and refined.

2. METHODOLOGY

2.1 STUDYING THE EFFECTS OF BRACKEN CONTROL MEASURES ON ARCHAEOLOGICAL REMAINS

The purpose of this research was to study how bracken control methods affect archaeological remains, by investigating how a number of bracken control methods affect part-buried, proxy archaeological remains (concrete cylinders – described in more detail in section 2.1.2, below). It also studied the effectiveness of the bracken control methods *per-se*. The effects of bracken control methods on archaeological remains were studied at sites on three farms; two in Northumberland (Ingram Farm, Fawdon Farm) and one in Devon (Challacombe Farm). The locations of the study sites are shown in figure 1, below. Ingram Farm formed the basis of an earlier study between 2011 and 2014, so bracken control treatments have been in place at a number of plots since 2011.

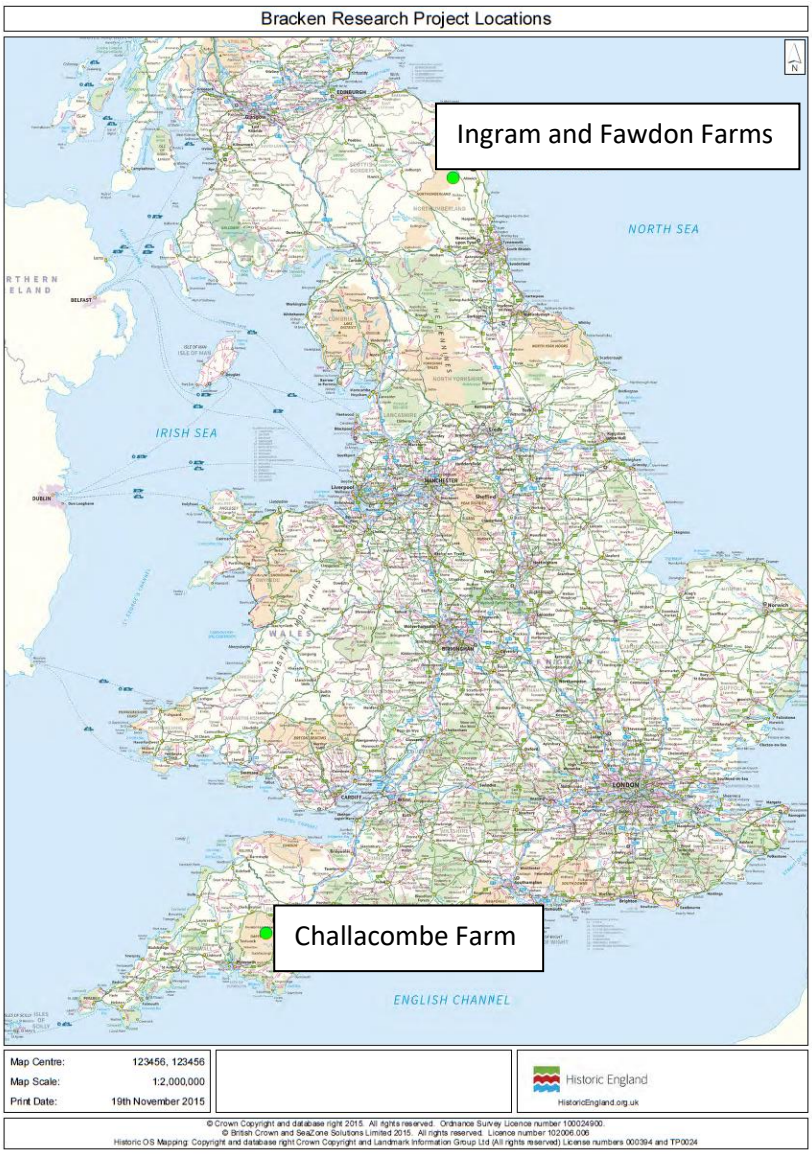

Figure 1. Study locations in England

2.1.1 *THE BRACKEN TREATMENTS, SITES AND EXPERIMENTAL SETUP*

This research is based on plot experiments at each of the three farms, which were used collectively to investigate mechanical bracken control, control by winter foddering of cattle, liming and control using herbicides. The plots for mechanical and liming treatments ranged in size and shape, but were approximately 0.3ha in area. The plots for chemical treatments measured up to 6m x 15m. Plot locations and treatments are described in more detail below.

Ingram Farm, Northumberland (mechanical and grazing treatments plus Control plots)

The plots at Ingram Farm were located on two hills, Wether Hill and Ewe Hill (see figure 2, below). Plots 1-2, 5-7 (Ewe Hill) and 9-14 (Wether Hill) had been undergoing bracken control treatments since 2011. Plots 3, 4 and 8 (Ewe Hill) were new additions to the experiment in 2016.

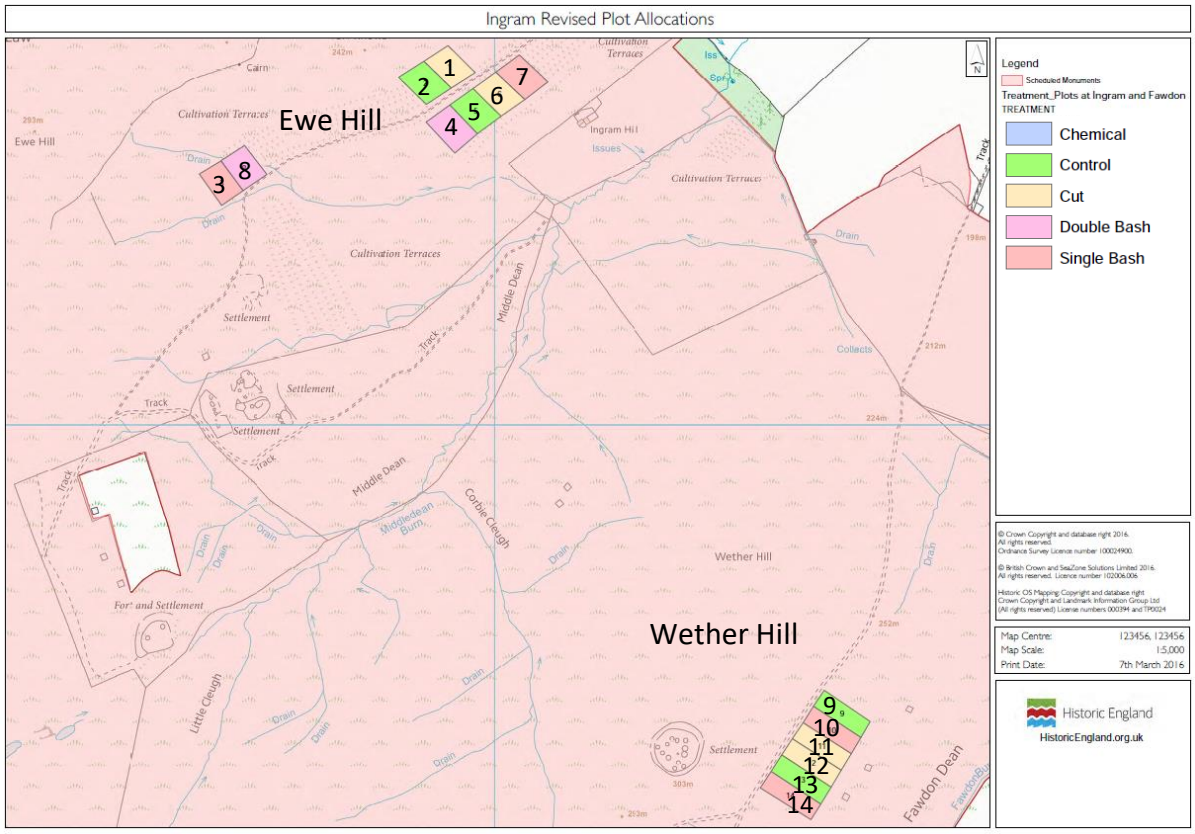

Figure 2. Mechanical and grazing treatment plots at Ingram Farm, Northumberland

With the exception of a five-week period from November 21st, the plots at Ingram Farm were open all year to hill grazing by Scottish Blackface sheep, running with their lambs April-September. Plots 1-8 (Ewe Hill) were grazed at a density of 1.91 ewe per ha and plots 9-14 (Wether Hill) were grazed at a density of 2. 1 ewe per ha. In winter, plots 9-14 on Wether Hill were also grazed by Aberdeen Angus cattle at 0.26 cattle per ha.

A cattle foddering treatment was applied on plots 9-14 from December-March, with two round bales of hay put out each day in the upper part of the plot where the ground is flatter and accessible from the track. A feed ring was not used, as this would have caused a large amount of trampling in a very small area. In order to encourage a more dispersed effect of the cattle foddering, the bales were rolled out.

Mechanical control treatments were applied to the plots established in 2011 and plot 3 established in 2016. Wether Hill (winter cattle foddering) and Ewe Hill (no winter cattle foddering) each had two replicates of a cutting treatment and a bashing treatment, plus two Controls. An additional mechanical treatment; double-bashing was applied to two of the newly established plots (4 & 8) on Ewe Hill. Details of the treatments are given below:

- Bashing: Using a quad towed bracken basher in late July each year 2011-2018 (see figure 3i & ii, below).
- Double bashing: Using a quad towed bracken basher in mid-June 2017 and 2018[1], or as soon as the fronds are sufficiently tall for treatment and preferably while they are still unfurling, followed by a second bashing treatment which took place once any re-growth of ferns was tall enough to bash or by September at the latest (see figure 3i & ii, below).
- Cutting: Using a tractor towed topper in late July each year in 2011-2018 (see figure 3iii, below).

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Figure 3. (i) Bracken bashing at Ingram Farm, Northumberland, (ii) Bracken basher and (iii) tractor-mounted cutter in use at Ingram Farm, Northumberland

[1] In 2018, the first bashing at plot 4 at Ingram Farm, Northumberland was undertaken two weeks later than usual because of ground nesting bird activity in the plot. An exclusion zone around each nest was established and none of this area was bashed at the first bash date.

Fawdon Farm, Northumberland (chemical treatments plus Control plots)

The chemical treatment plots (plus Control treatments) at Fawdon Farm are located on a north-facing slope along a strip towards the bottom of East Hill, above the River Breamish (see figure 4, below). The strip was subdivided to receive different chemical treatments, with seven replicates of five treatments in small plots spread across the site, separated by a 4m (minimum) buffer. The standard plot size was 6m x 10m, with fifteen plots extended to 6m x 15m so a 5m-wide strip at one end could be used for insertion and monitoring the proxy archaeological remains (section 2.1.6, below). This was undertaken to avoid impinging on the National Chemical Bracken Control Trials Programme being carried out by R & D Applied Biology.

Two Control plots were excluded because spray drift caused extensive damage to the bracken in 2016.

The treatments, applied in early September 2016, were:

- Asulam 1N
- Amidosulfuron 1N
- Amidosulfuron 0.5N (half strength)
- Metsulfuron 1N
- Control

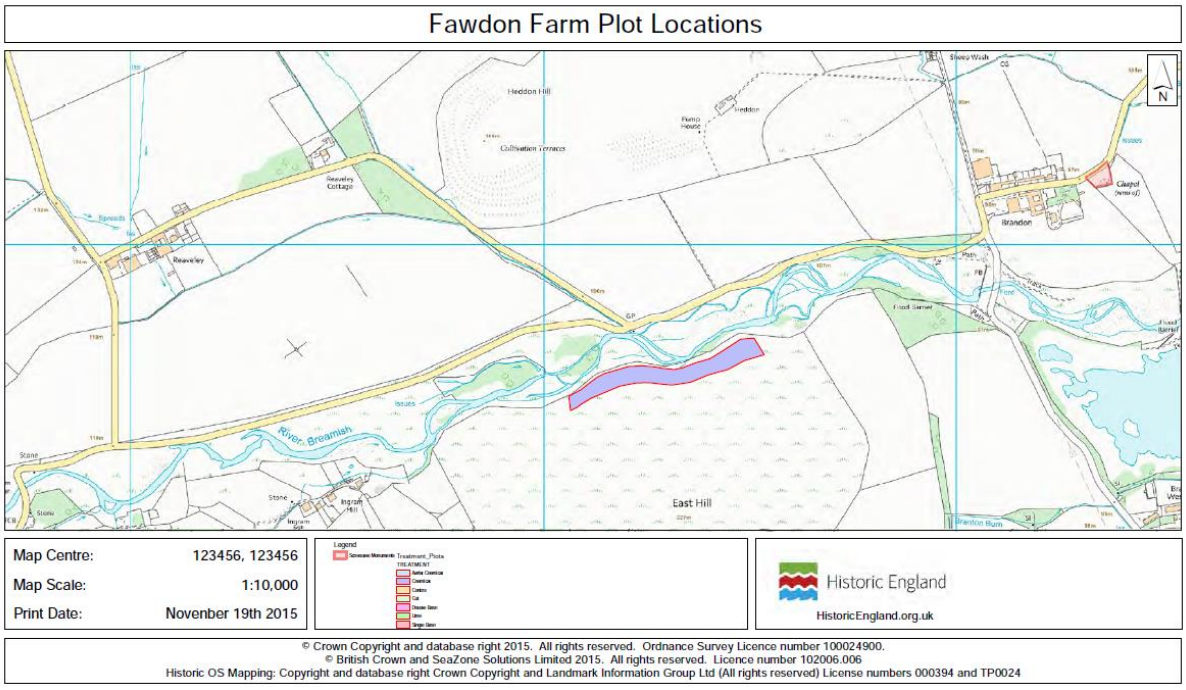

Figure 4. Chemical treatment site at Fawdon Farm, Northumberland (plots are set out within the purple polygon)

Challacombe Farm, Devon (mechanical, liming and chemical treatments plus Control plots)

The plots at Challacombe Farm were located within mediaeval field boundaries on Challacombe Down (figure 5, below), and were initially open to extensive grazing by sheep and wild ponies. Plots 2-11 formed the mechanical control/liming trial, with two fields assigned to each treatment.

Fields 1 and 12 were used for small-plot chemical treatment trials. These comprised 12 replicates of 5 treatments (see below). Thirty plots per field were set out, avoiding likely sites of archaeological remains. The standard plot size was 6m x 10m separated by a minimum 4m wide buffer. Five plots in each field were extended to 6m x 15m to allow a 5m-wide strip at one end for insertion and monitoring of the proxy archaeological remains (section 2.1.6, below). This was undertaken to avoid impinging on the National Chemical Bracken Control Trials Programme being carried out by R & D Applied Biology.

In winter 2018/19, the field system was fenced off from the surrounding down to address an issue unrelated to this project.

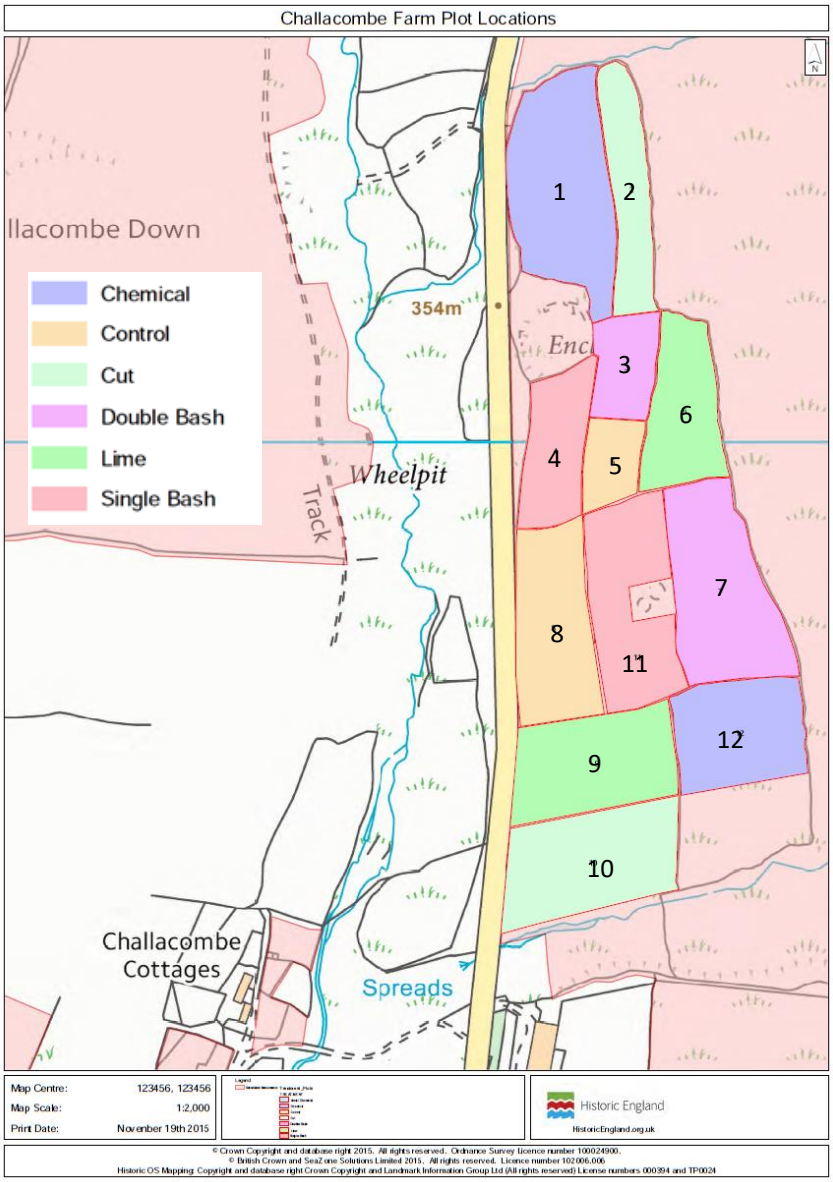

Figure 5. Mechanical, liming and chemical treatment plots at Challacombe Farm, Devon

Mechanical and liming treatments at Challacombe Farm

The mechanical treatments at Challacombe Farm were similar to those at Ingram Farm, Northumberland, with the addition of a Liming treatment. Two plots per treatment were set out at Challacombe Farm, and treatments carried out as follows:

- Bashing: Using a quad towed bracken basher in late July each year in 2016-2018 (see figure 6, below).
- Double bashing: Using a quad towed bracken basher in mid-June 2017 and 2018, or as soon as the fronds were sufficiently tall for treatment and while they were still unfurling. This was followed by a second bashing treatment which took place once any re-growth of ferns was tall enough to bash, or by September at the latest.
- Cutting: Undertaken using a tractor or quad towed topper and brushcutter (depending on topography), annually in late July. Plot 2 was not suitable for cutting by tractor so in 2016 was cut (close to ground level) using a brushcutter and in 2017 was cut using quad towed topper, to a height of approximately 10cm. Plot 10 was cut to a height of approximately 10cm using a tractor towed topper.
- Liming: Application in late summer/autumn 2016 at a rate sufficient to raise the pH. to 6. The liming application was undertaken on foot or from a tractor, depending on topography. Plot 6 was limed on foot, with the lime carried in buckets and spread by hand. Plot 9 was limed from a tractor, making two passes, each approximately 10m apart to ensure an even spread of lime.

Figure 6. Bracken bashing at Challacombe Farm, Devon. Photo: Mark Owen

Chemical bracken treatments at Challacombe Farm

In parallel with the experiment at Fawdon Farm, the treatments applied in early September 2016 were:

- Asulam 1N
- Amidosulfuron 1N
- Amidosulfuron 0.5N (half strength)
- Metsulfuron 1N
- Control

2.1.2 MEASURING BRACKEN COVER, DENSITY AND VIGOUR

Measures of bracken cover, density and vigour for each plot at Ingram Farm were assessed annually in July by recording within five $1m^2$ quadrats per plot. Quadrats were recorded at 10-15m intervals along a transect down the centre of each plot's long axis. The first and last quadrats in each transect were located at least 10m from the edge of the plot.

A sister project undertaken by R & D Applied Biology oversaw collection of vegetation data from the plots at Fawdon Farm, Northumberland and Challacombe Farm, Devon (2016 and 2017). In 2018 and 2019 data collection continued under the administration of Ketmar using the same methodology. In the chemical treatment plots at Fawdon and Challacombe farms, the whole plot was used for assessments of bracken, and in the physical/liming plots at Challacombe Farm, ten $1m^2$ quadrats were randomly placed within each plot. Data were collected annually in July from the Challacombe Farm physical/liming treatment plots and in July-mid-August from the chemical trials at Challacombe and Fawdon farms.

Percentage cover of bracken was recorded to the nearest 5%. Bracken cover in any quadrats with an estimated cover of less than 5% were recorded to an estimate of the nearest percentage point. Additional bracken measurements were taken to assess height, vigour and density of bracken cover within each quadrat. The measurements are detailed below:

- Bracken density: The number of living shoots within the $1m^2$ quadrat.
- Bracken frond height: the maximum height of the stand within the quadrat, measured to the nearest cm. At Ingram Farm, Northumberland this was recorded as the mean of the three tallest fronds arising within the quadrat. At Fawdon Farm, Northumberland this was recorded as the mean of the ten tallest fronds arising within the plot. In the chemical trial plots at Challacombe Farm, Devon this was recorded as the mean of the five tallest fronds arising within the plot. In the physical/liming plots at Challacombe Farm, Devon this was recorded as the mean of the ten tallest fronds arising within each quadrat.
- Bracken vigour: This is a 10-point scale used by Scott *et al* (1994), where bracken vigour score is based on the best estimate of each of four criteria; an assessment of bracken condition, cover percentage, average height of the bracken stand and shoot density as described above. The criteria for scoring bracken vigour are shown in table 1, below.

Vigour score	Condition	Cover	Height	Shoot density (shoots m^{-1})
1	Poor or very young	5-20%	25-50 cm	1-30
2	Poor or young	10-50%	35-60 cm	5-50
3	Poor or young	25-70%	45-70 cm	10-55
4	Moderate	40-90%	50-75 cm	15-55
5	Moderate	55-95%	55-85 cm	15-65
6	Moderate	70-95%	60-90 cm	15-70
7	Good	75-100%	65-100 cm	15-70
8	Good	85-100%	70-115 cm	15-70
9	Good	90-100%	80-130 cm	15-70
10	Good	98-100%	100-175 cm	15-70

Table 1. The bracken vigour scale – descriptions and criteria

2.1.3 *UNDERSTOREY VEGETATION DYNAMICS AND LITTER*

Ingram Farm, Northumberland

The understorey vegetation in each plot at Ingram Farm was assessed annually in July in the same quadrats described in section 2.1.2 above. In each quadrat, cover of all vascular plant and bryophyte species present was recorded. Species with an estimated cover of less than 5% were recorded to the nearest percentage point. Species whose cover was greater than 5% were recorded to the nearest 5%. Measurements of litter were also taken in the quadrats at Ingram Farm using the methodology described above. Litter depth was recorded to the nearest centimetre, as the mean of three measurements taken by probe at random points within the quadrat.

Challacombe Farm, Devon & Fawdon Farm, Northumberland

Collection of understorey vegetation and litter percentage cover at Challacombe and Fawdon farms was undertaken as part of a sister project by R & D Applied Biology in 2016-2017 then overseen by Ketmar 2018-2019. Data were collected using the same sampling methodology as the bracken cover data for those sites (section 2.1.2, above).

In 2016 at the Challacombe Farm physical/liming and chemical trials and Fawdon Farm chemical trial, understorey cover was recorded as one measure and species richness as another. In 2017, cover of grasses was recorded as one measure and all other species recorded individually, all to the nearest percent cover. From 2018-2019 cover of all understory species was recorded to the nearest percent.

2.1.4 *ANALYSIS OF VEGETATION COMMUNITIES USING THE NATIONAL VEGETATION CLASSIFICATION*

The National Vegetation Classification (NVC, Rodwell, 1990-2000) provides a framework for categorisation of vegetation communities in Great Britain. Descriptions for 256 communities exist, spread across 12 major categories, of which one; calcifugous grasslands and montane communities (prefixed 'U' followed by a number or number and a letter) is relevant to the study at Ingram Farm.

The bracken-dominated vegetation found in the plots at Ingram Farm has previously been categorised as a fit to U20 acid grassland communities and sub-communities U20a, U20b and U20c. The vegetation in plots at Ingram Farm which are dominated by grasses have previously been categorised as U4b acid grassland sub-community (Scott *et al* 2015). Categorisation of the 2016 plot data to NVC communities was again based on a fit to acid grassland NVC communities and sub-communities. The calcifugous grassland and montane communities and sub-communities which were considered as potentially suitable matches are described as follows:

- U20*: Pteridium aquilinum - Galium saxatile* community.
- U20a: *Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community.
- U20b: *Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community.
- U20c: *Pteridium aquilinum – Galium saxatile*; species-poor sub-community.
- U1f: *Festuca ovina-Agrostis capillaris-Rumex acetosella* grassland; *Hypochoeris radicata* sub-community.
- U4: *Festuca ovina - Agrostis capillaris - Galium saxatile* grassland.
- U4b: *Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community.

Vegetation data from the quadrats in each plot were averaged and matched to NVC communities or sub-communities using Tablefit software (Hill, 2015). Tablefit produces a goodness of fit score for a number of possible NVC communities. Descriptions of scores from 1-100 are as follows:

- 70-100 - Very Good
- 50-69 - Good
- 40-49 - Fair
- 30-39 - Poor
- 01-29 - Very Poor

2.1.5 *ANALYSIS OF SPECIES AND ENVIRONMENTAL DATA*

A number of analyses were carried out to test for differences between treatments. Most tests used ANOVA and Tukey's range test, undertaken with the aov and TukeyHSD packages of the statistical analysis software R.

For instances where variance of the quadrat cover data (%) was observed to increase with the mean, the quadrat data were arcsine transformed prior to undertaking the ANOVA test. Arcsine transformation involves taking the arcsine of the square root of the percentage cover expressed as a proportion. In the case of the total cover and understorey cover, which often exceeded 100%, the data were re-based to express each as a proportion of the highest value before undertaking the arcsine transformation.

Bracken vigour scores were compared for statistically significant differences between treatments using the Kruskal Wallis test and Dunn post-hoc tests in the statistical analysis software R.

2.1.6 STUDYING THE EFFECTS OF BRACKEN TREATMENT ON ARCHAEOLOGICAL REMAINS AND THE HISTORIC ENVIRONMENT

There were three elements to this part of the study; the use of part-buried concrete cylinders as a proxy for archaeological remains, recording environmental data as part of the vegetation quadrat survey and measurement of changes in ground height using an unmanned aerial vehicle (UAV). The methodology for each of these elements is described below.

Installation of proxy archaeological remains

In order to understand how bracken control measures affect archaeological remains, in late May and early June 2016, nine pre-cast concrete cylinders were part-buried in each plot at Ingram Farm, Fawdon Farm and Challacombe Farm, to simulate archaeological remains. Changes to the position and condition of each were monitored annually to assess whether their location and condition were affected by the different treatments.

Each cylinder measured 10cm diameter and was 15cm tall. The cylinders were painted with white masonry paint to provide a visual contrast to the surrounding vegetation, making them easier to find if they were displaced. The paint also acted as a barrier between the concrete surface and surrounding soil and vegetation. The cylinders were cast with a brightly painted clout nail in the centre of the top edge to act as a survey point.

The nine concrete cylinders installed in each treatment plot were arranged in a square grid, 1m apart along the perpendicular axes (see figure 7, below). Each cylinder was placed in a hole excavated by an auger, approximately 10cm deep so as to protrude between 50mm-80mm. The cylinders were installed according to the surrounding topology so that the extent to which they protruded was more or less equal all the way round. Each concrete cylinder was installed in a way intended to ensure that the cylinder was stable, while attempting to preserve the integrity and density of surrounding litter, soil and bracken rhizomes.

Each cylinder in the grid was individually labelled on the top surface using a paint marker. Cylinders were labelled with the plot number (and sub-plot number for chemical treatments in plots 1 and 12 at Challacombe Farm, Devon) and a letter from a-i.

The grids were orientated according to the four compass stations, such that ‘a’ was in the north-west corner and ‘i’ was in the south-east corner (see figure 7i).

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Figure 7. (i) Diagrammatic example of concrete cylinders showing labelling for plot 2 and (ii) photograph of cylinders in situ

Measuring the positions and orientation of the proxy archaeological remains

The marked centre-point of each buried cylinder was surveyed with a Leica TCR805 Total Station (5" accuracy), based from an established control network (see section 2.2.1, below). Following a site survey at the project locations, all datasets were fully georeferenced and integrated within a project-specific geographic information system (GIS) using Quantum GIS (QGIS) software.

In order to capture data to assist understanding of micro-scale movements of the cylinders over time, the horizontal orientation of each cylinder top was measured using the Surface mobile application, (developed by Ofijo) on an IPhone 5s. Measurements were recorded as degrees of tilt from the horizontal, relative to north-south and east-west. An example of the application in use is shown in figure 8, below.

The concrete cylinder displacement data were categorised according to extent of displacement, on a scale of 1-14. Cylinders still within their hole were scored between 1-8 depending on the extent of movement from the original position. The scoring was calculated as follows:

Changes in tilt were scored 1-8 according to the number of degrees change in tilt angle, in 10-degree increments. Changes in azimuth were scored from 1-8 in eight 20-degree increments starting from 41 degrees. The highest score for a cylinders' change in tilt or azimuth was then selected as the displacement score for that cylinder.

Cylinders that had been displaced from the hole were scored 9-14 depending on the distance from original position that the cylinder had travelled by 2019. Cylinders that had been displaced up to 50cm were scored as 9 and so on in 50cm increments to a maximum of 14 for cylinders displaced more than 2.5m.

The data were then analysed using the using the Kruskal Wallis test and Dunn post-hoc tests in the statistical analysis software R.

Figure 8. Photograph of the Surface app in use on top of one of the concrete cylinders. Inset: angles measured in x (west-east) and y (north-south) planes

Visual assessment of damage to the simulated archaeological remains

Damage to the concrete cylinders was assessed visually each May 2017-2019. Cylinders were recorded as having been damaged if there were any signs of damage beyond slight crumbling or paint loss at the edges which might be attributed to weathering and erosion. The damaged cylinders were photographed to allow differentiation between damage to date and any damage in future.

Recording environmental data as part of the vegetation quadrat survey

Assessments of damage to the historic environment were made at Ingram Farm, Northumberland (only), by taking the following measurements in each quadrat:

- Bare ground: Percentage cover of bare ground within the quadrat (Ingram Farm only).
- Disturbed ground: Percentage cover of visually disturbed ground within each quadrat. This assessment generally overlapped with the assessment of bare ground (Ingram Farm only).
- Stones: Percentage cover of exposed stones within the quadrat (Ingram Farm only).

Measuring changes in ground height using an unmanned aerial vehicle

An unmanned aerial vehicle (UAV) was used to collect data for measuring changes in ground height over time. The purpose of this was to assess the efficacy of UAV surveys for understanding damage to the historic environment as a result of bracken control. The data capture and analysis was undertaken for Historic England by TerraDrone. Data capture took place in May 2016 and 2019 using a GPS-equipped Falcon 8 multi-rotor UAV equipped with a Sony a7R camera. Analysis of ground height changes was carried out using the Zonal Statistics tool in QGIS to calculate the mean, median, minimum, maximum and range of ground height change for each plot.

2.2 ADDITIONAL, TECHNICAL UNDERTAKINGS

2.2.1 *SETTING OUT THE SURVEY NETWORK*

Initial survey control was established with a site datum located using a Leica Smartrover survey-grade NRTK GPS with an accuracy of ±10 mm; this level of accuracy was confirmed during set-up by resurveying of intervisible station points with a Leica TCR805 Total Station (5" accuracy). Control stations from the previous survey were identified and where relevant to the current project, re-surveyed to ensure parity and accuracy across the control network. For each group of plots, station points were placed at the corners of all plot groups, and a further two 'redundancy' station points were established with visibility across all plots. Station points were marked with 300mm steel and polyethylene survey ground markers with high-visibility polyethylene caps to ensure both ease of location and permanency through the life of the project. The corners of all treatment sub-plots were also marked with *c*. 40 cm high wooden stakes stained with yellow high-visibility paint. These were accurately positioned using a Leica Smartrover survey-grade NRTK GPS at the points given within the experiment design provided by Historic England.

At the Fawdon chemical treatment plots and for all the Challacombe plots, the corners or limits of the plots were not marked out given their irregularity. At these sites a control network was established based on local topography and ensuring multiple intervisible station points for each buried concrete cylinder grid.

2.2.2 *MEASURING BRACKEN EXTENT USING GPS AND A UAV IN PLOTS AT INGRAM FARM, NORTHUMBERLAND*

A secondary aim of this project was to compare the methodology and findings of ground-based, GPS measurements of bracken extent, alongside remotely-sensed bracken cover data collected using an unmanned aerial vehicle (UAV). This was to evaluate their potential as tools for monitoring the effectiveness of bracken control.

The UAV data collection and analysis were carried out by TerraDrone at Ingram Farm, Fawdon Farm and Challacombe Farm. The ground-based bracken mapping was carried out at Ingram Farm. Each methodology is described below.

Ground-based bracken mapping at Ingram Farm, Northumberland

Bracken extent in each plot at Ingram Farm was mapped during July 2016 & 2017 using an Ashtech Mobilemapper 6 GPS and in July 2018 & 2019 using a Leica Zeno 5 GPS. The mapping exercise focused on capturing the extent of bracken at 100% cover with a vigour score of 7 or above, to an accuracy of 1m. The bracken was mapped by walking the perimeter of the bracken 'front' around and within each group of plots, to capture an initial bracken extent polygon. This was followed up by walking the perimeters of bracken 'fronts' along paths or other gaps within the plots where bracken was absent or below 100% and vigour score 7.

UAV-based bracken mapping at Ingram Farm, Northumberland

The UAV multispectral surveys of were carried out in July 2019 using a MicaSense camera, capturing Band 3 and Band 4 wavelengths. Band 3 wavelengths (green, 0.53-0.59 micrometres) are best suited to assessing plant vigour. Band 4 wavelengths (red, 0.64-0.67 micrometres) are best suited to differentiating between vegetation types.

The data were then processed in SAGA GIS to calculate the normalised difference vegetation index (NDVI) using the Vegetation Index (Slope Based) tool. The NDVI identifies live green vegetation in the data. The data were then analysed on a plot by plot basis to assess the mean, median, minimum, maximum and standard deviation of the NDVI values using the zonal statistics plugin in QGIS.

3. RESULTS

This section presents a summary of the analysis of changes in bracken vigour, understorey vegetation and bracken mapping, plus analysis of damage and displacement of the ground in the plots and the concrete cylinders. Appendices 6.1-6.5 provide additional figures and output from the hypothesis tests used below.

3.1 BRACKEN VIGOUR

3.1.1 *BRACKEN VIGOUR AT EXPERIMENTAL PLOTS ESTABLISHED IN 2011 AT INGRAM FARM, NORTHUMBERLAND*

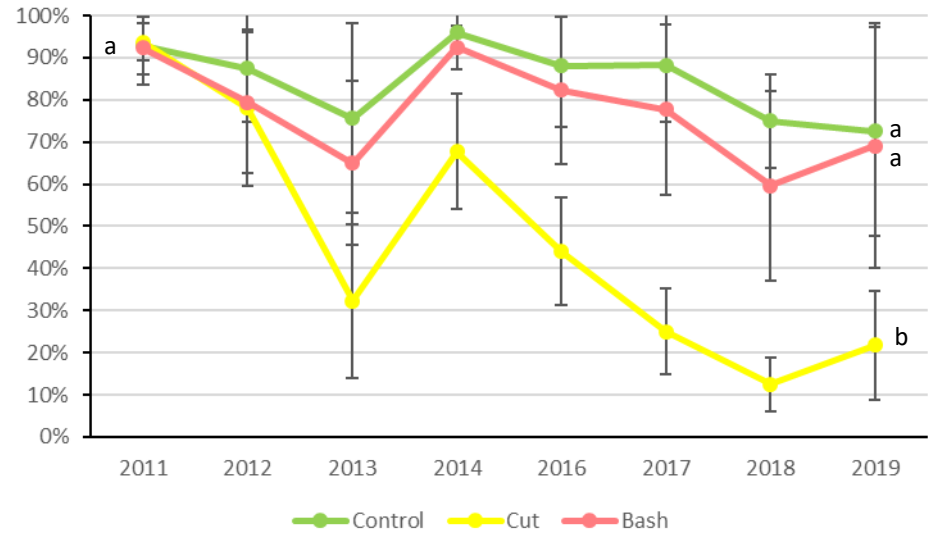
This section compares, by treatment, the percentage bracken cover, height, frond density and bracken vigour scores collected by Archaeological Research Services Ltd in 2011-14 and Ketmar in 2016-19 (figures 9-12). No data were collected at Ingram Farm in 2015, although the treatments were still applied.

In 2018, the hot and dry weather in early summer had a noticeable effect on the appearance of the bracken, with a number of fronds showing signs of early senescence by the time quadrat data were collected.

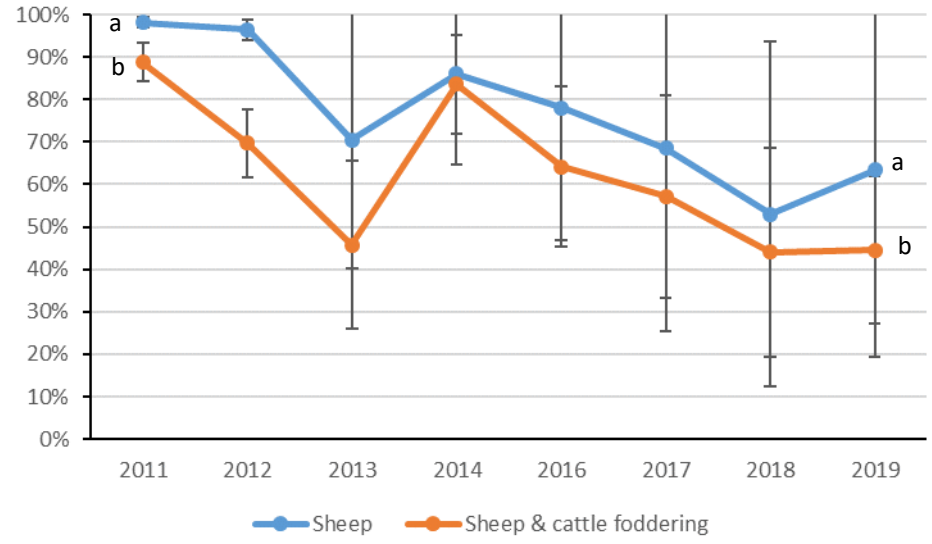
By 2019 there were a number of significant differences in measures of bracken between the Cut and other treatments, with bracken *cover*, mean frond *height*, frond *density* and *vigour* scores all significantly lower in the Cut treatment compared with the Bash and the Control treatments (figures 9i, 10i, 11i & 12i, below ($P < 0.001$)). In 2019, the Bash treatment also had significantly lower frond height than the Control (figure 10i, ($P < 0.01$))

In 2019 bracken on the plots with grazing plus winter cattle foddering vs. grazing without cattle foddering had significantly lower bracken *cover* (figure 9ii ($P < 0.001$)), *frond height* (figure 10ii ($P < 0.001$)) and consequently, *vigour* score (figure 12ii ($P < 0.05$)). There was no significant difference in frond *density* (figure 11ii). However, bracken *vigour* was initially higher on the plots designated to receive the cattle foddering treatment ($P < 0.01$).

There were interactions between the cattle-foddering treatment and mechanical treatments, so further analyses were carried out to compare the effect of cattle foddering on the Controls, where no mechanical treatments took place. There was no significant difference between bracken *cover* and *frond height* in the Control plots on Wether Hill and Ewe Hill at the start of the experiment in 2011. By 2019, bracken *cover* and *frond height* were significantly lower where winter cattle foddering had taken place (both $P < 0.001$). Consequently, bracken *vigour* was also significantly lower where there had been winter cattle foddering ($P < 0.001$).

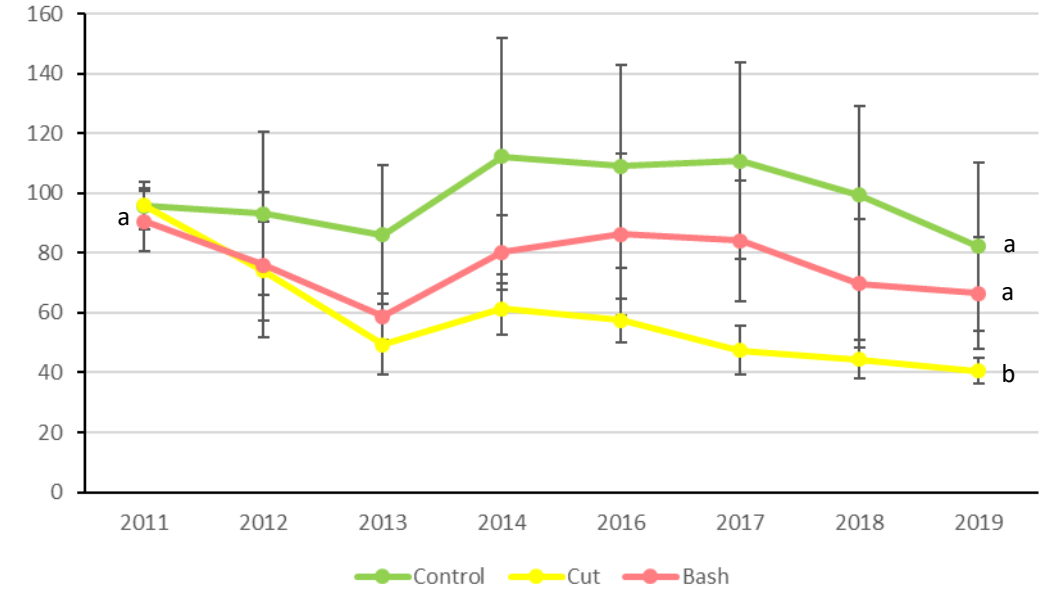


i

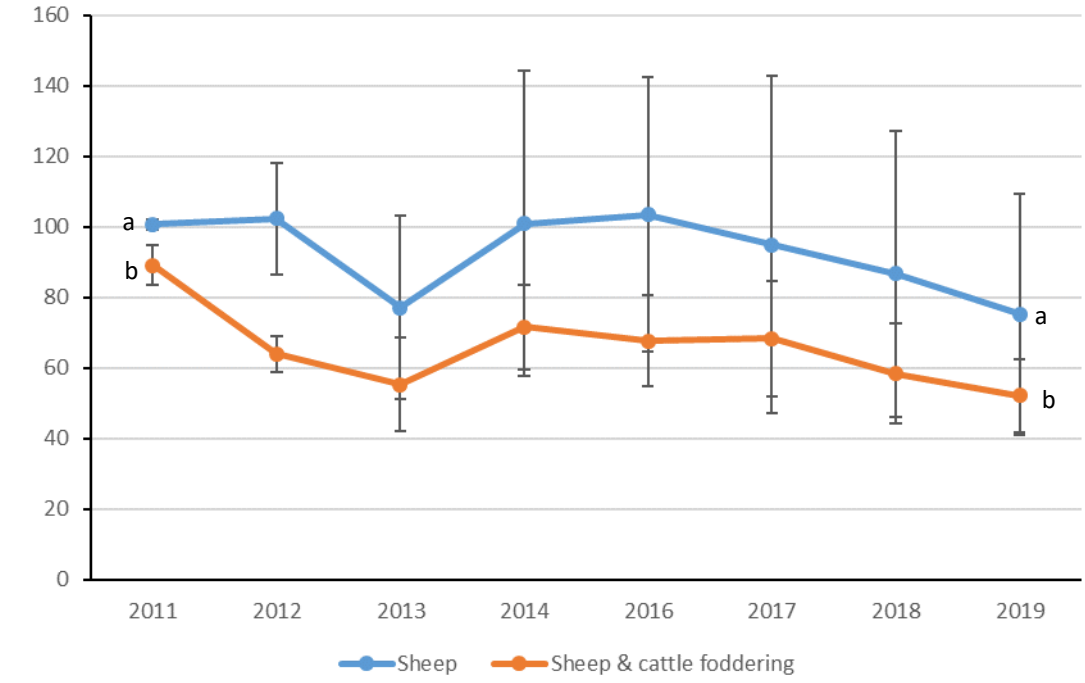


ii

Figure 9. Mean (± standard deviation) cover (%) of bracken at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016

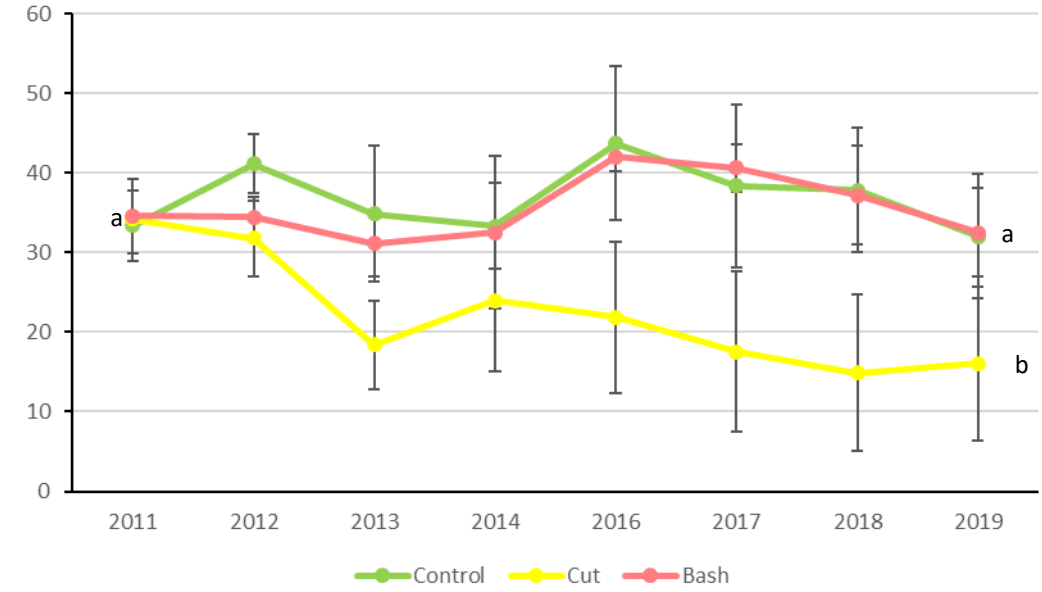


i

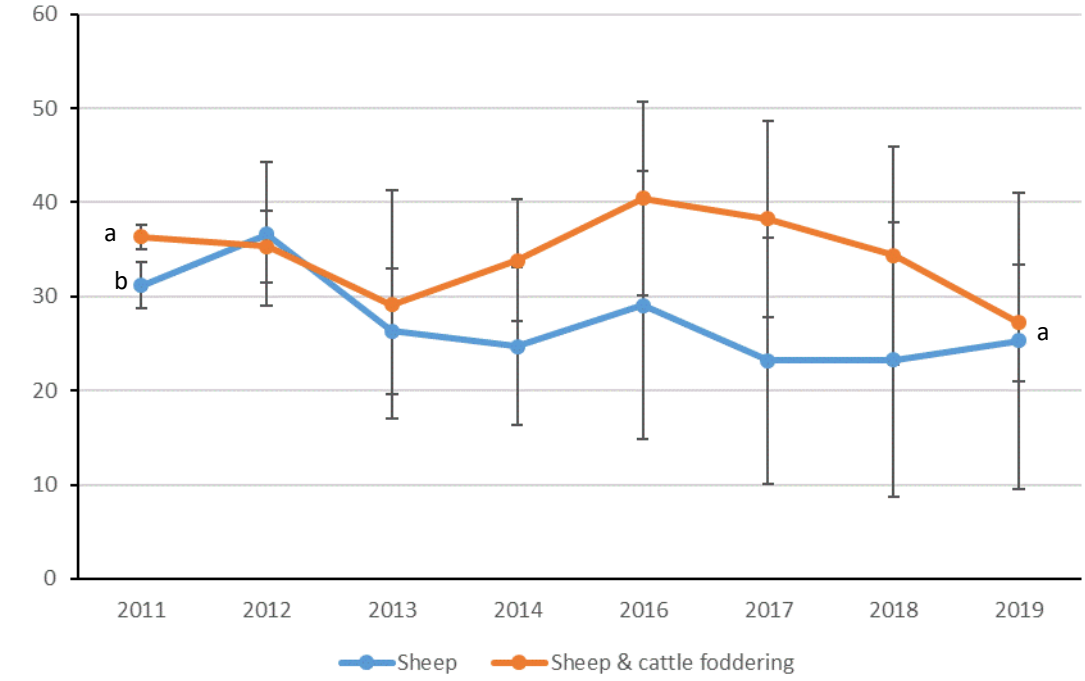


ii

Figure 10. Mean (± standard deviation) bracken frond height (cm) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016

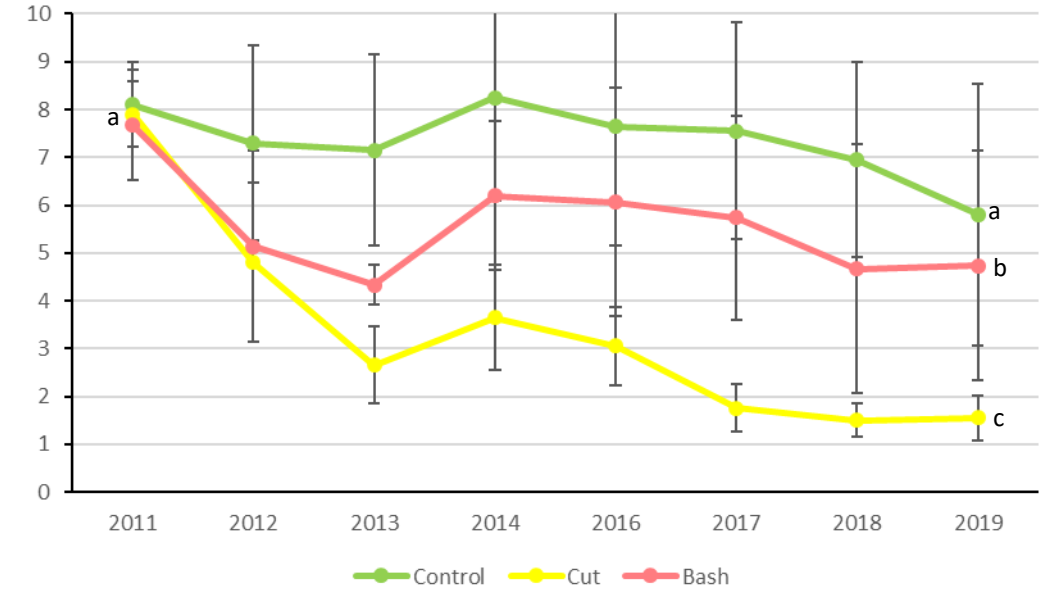


i

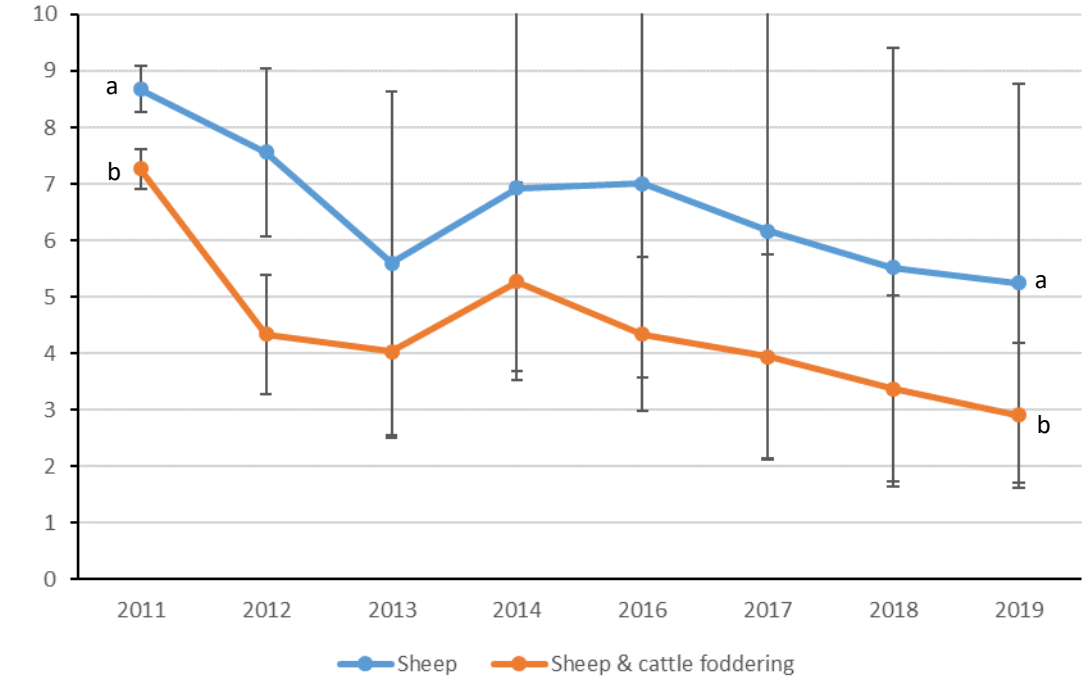


ii

Figure 11. Mean (± standard deviation) bracken frond density (live fronds per m^2) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii)



i



ii

Figure 12. Mean (± standard deviation) bracken vigour score (1-10) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016

3.1.2 *BRACKEN VIGOUR AT NEW EXPERIMENTAL PLOTS AT INGRAM FARM, NORTHUMBERLAND*

This section presents findings from data collected by Ketmar in 2016-19.

The experimental plots established in 2016 on Ewe Hill, Ingram Farm were set out in stands of bracken and understorey intended to be comparable with that found in the existing Control plots. In 2016 bracken cover was high in all plots (figure 13, below). However, the pre-treatment (2016) data showed that bracken *cover* in the new Bash treatment plot was significantly lower than in the Control plots ($P < 0.001$) and pre-treatment Double-bash treatment plots ($P < 0.05$) on Ewe Hill.

In 2016, prior to any treatments being applied, the other measures of bracken vigour (mean bracken *frond height* and number of living *bracken shoots per m*^{2}) were comparable between the new plots and the Control plots on Ewe Hill (figures 14 & 15, below). The exception to this was with the number of living *bracken shoots per m*^{2}, which was significantly lower in plot 3 (designated for Bash treatment) compared with the Control plot 2 ($P < 0.05$).

By 2017 and 2018, bracken *cover* in the Double-bash plots was significantly lower than the Control and newly established Bash treatment plot (figure 13, below, all $P < 0.001$). In each case the initial bash had been carried out several weeks prior to the vegetation survey. In 2018 the first bash in Double-bash plot 4 was delayed by two weeks to allow the offspring of ground-nesting birds to fledge from one corner of the plot. In 2019, treatments were not applied to the Double-bash plots, so for the first time 'residual' bracken *cover* for that treatment was recorded. Bracken *cover* in the Double bash treatment was not significantly lower than the Controls on Ewe Hill. In 2019, bracken *cover* in the newly established Bash plot was significantly lower than the Control ($P < 0.05$).

In 2019, mean frond height (figure 14, below) and bracken vigour scores (figure 16, below) were significantly lower in the Double-bash treatment (both $P < 0.001$) and Bash plot 3 (both $P < 0.01$) compared with the Control treatment on Ewe Hill.

The mean number of living bracken shoots was not significantly different between treatments (figure 15, below).

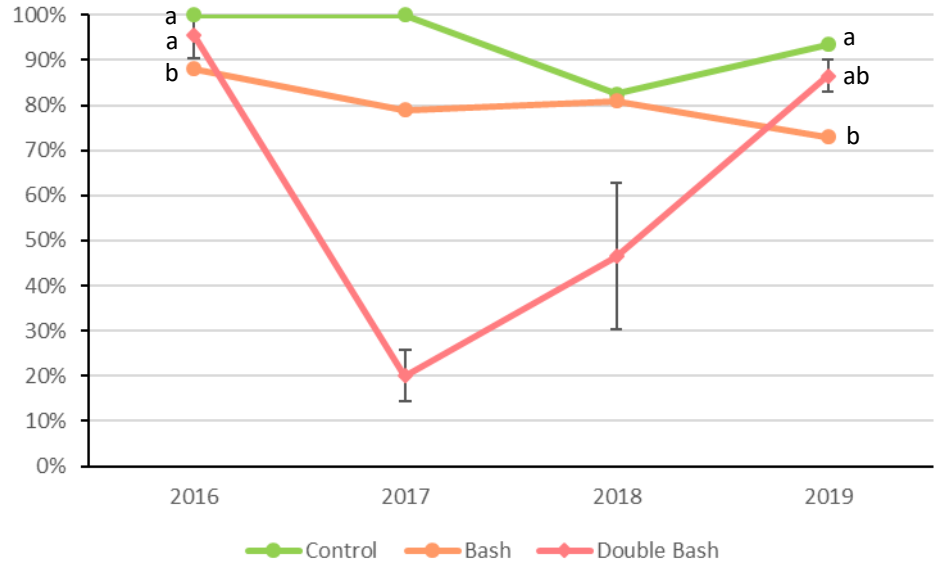


Figure 13. Mean (± standard deviation) cover (%) of bracken in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

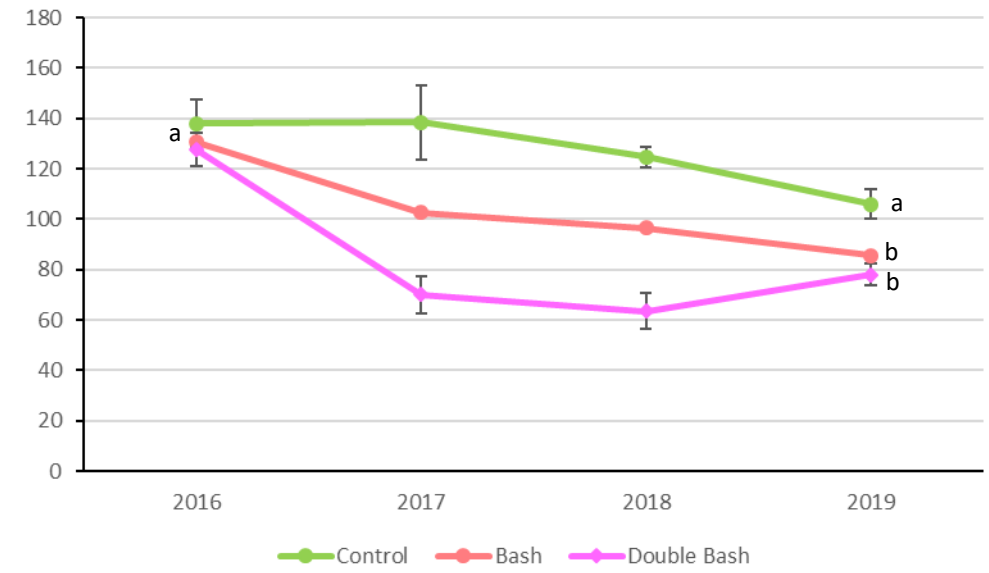


Figure 14. Mean (± standard deviation) of mean bracken frond height of tallest 3 fronds per quadrat in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

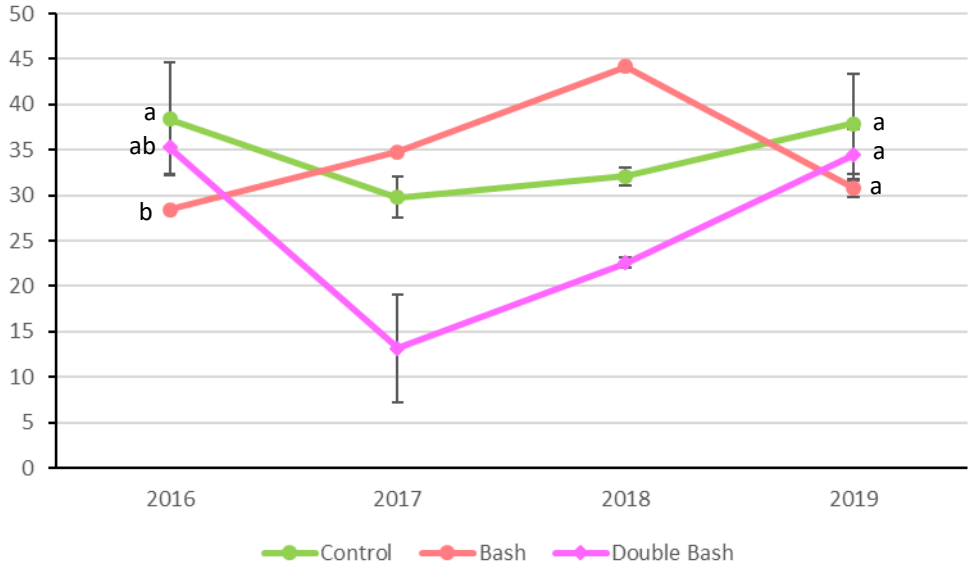


Figure 15. Mean number (± standard deviation) of living bracken shoots per m^2 in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

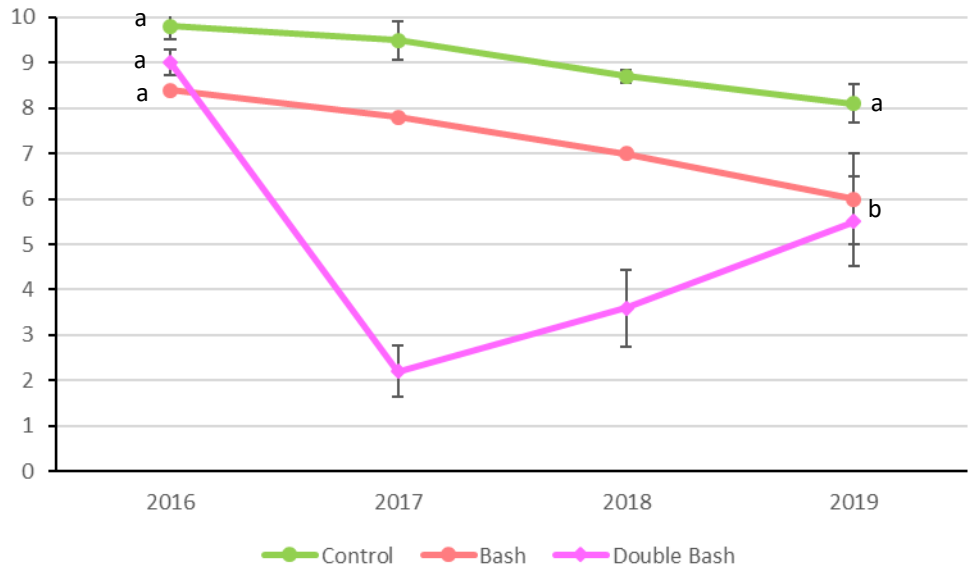


Figure 16. Mean (± standard deviation) bracken vigour score in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

3.1.3 *BRACKEN VIGOUR AT MECHANICAL/LIMING TREATMENT PLOTS, CHALLACOMBE FARM, DEVON*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

In the baseline year (2016) there were no significant differences in bracken *frond height* between treatments. By 2019, there were significant differences between most treatments (figure 19, below ($P < 0.001$)), the exceptions being Lime and Control, and the Double-bash vs Cut treatments. The Liming and Control treatments had the highest stands, followed by the Bash treatment, then the Cut and Double-bash treatment.

In 2016, the mean number of *living bracken shoots* (figure 18, below) was significantly higher in the Control plots compared with the Double-bash plots ($P < 0.05$) and the Lime treatment plots ($P < 0.01$). By 2019 there were several more significant differences between treatments. The number of *living bracken shoots* in the Liming and Control treatments were significantly lower than in the Double-bash plots (both $P < 0.001$) and the Bash plots (both $P < 0.01$). The Double-bash treatment also had significantly more *bracken shoots* than the Cut treatment ($P < 0.001$), and significantly less than the Bash treatment ($P < 0.001$).

In 2016, bracken *cover* (figure 17, below) was significantly higher in the Control plots compared with the Bash plots ($P < 0.01$), Cut plots ($P < 0.05$) and Double-bash ($P < 0.001$). Bracken cover in the Lime treatment plots were also significantly higher than the Bash plots ($P < 0.05$) and Double-bash plots ($P < 0.001$). In 2019, the differences in bracken *cover* between some treatments was more marked, with bracken *cover* again significantly higher in the Control plots compared with the Cut plots ($P < 0.001$) and Double-bash ($P < 0.001$), but the bracken *cover* in the Bash plots was not significantly different from the Control plots.

In 2016 there was no significant difference in bracken *vigour* scores between treatments (figure 20, below). By 2019 the Cut, Bash and Double-bash treatments were all significantly lower than the Control and Liming treatments ($P < 0.001$). Bracken *vigour* scores were also significantly lower in the Double-bash treatment compared with the Bash treatment ($P < 0.05$).

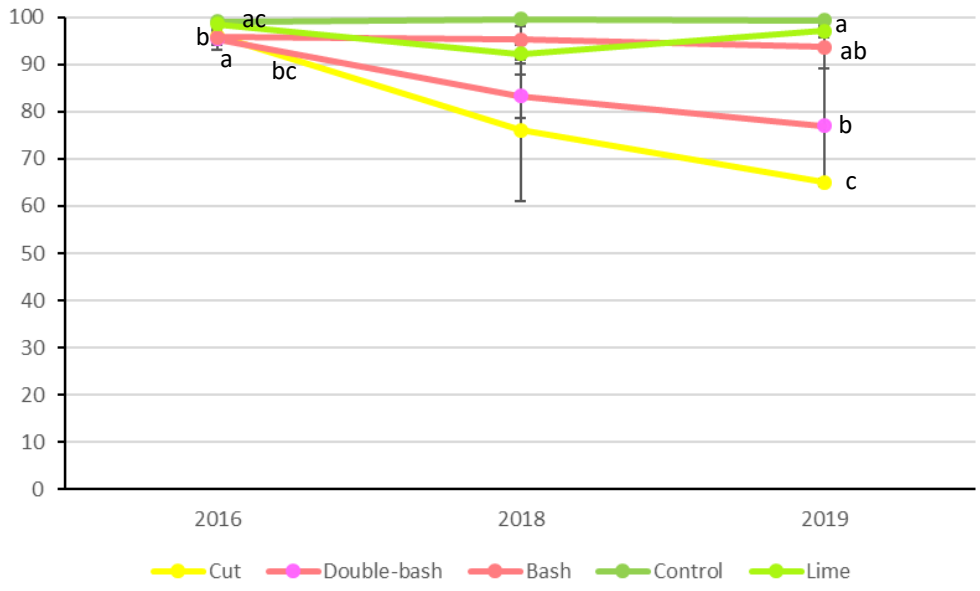


Figure 17. Mean (± standard deviation) cover (%) of bracken in mechanical/liming treatment plots at Challacombe Farm, Devon, 2016, 2018-2019

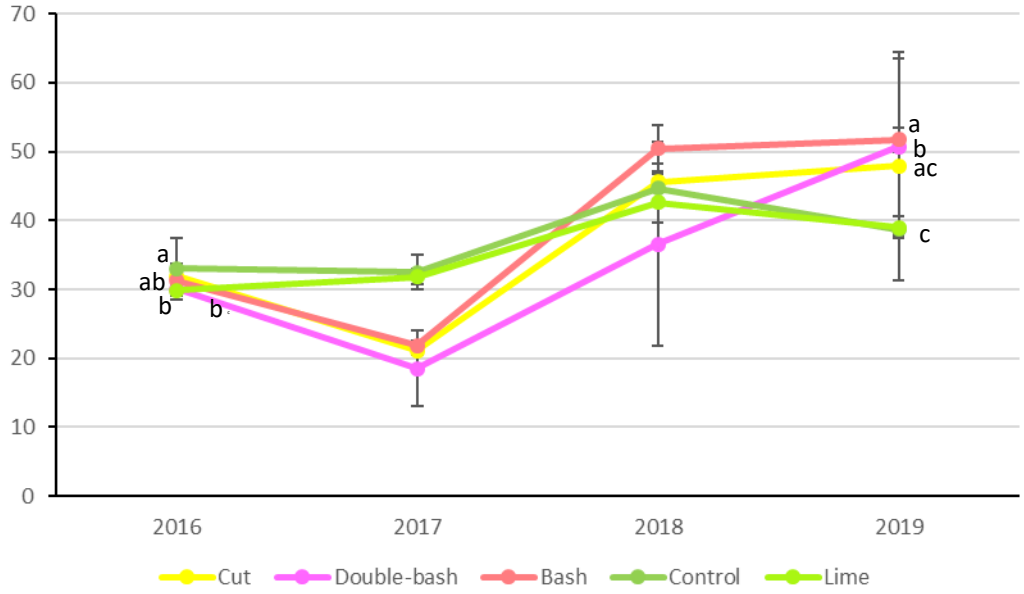


Figure 18. Mean number (± standard deviation) of living bracken shoots per m^2 in mechanical/liming treatment plots at Challacombe Farm, Devon, 2016-2019

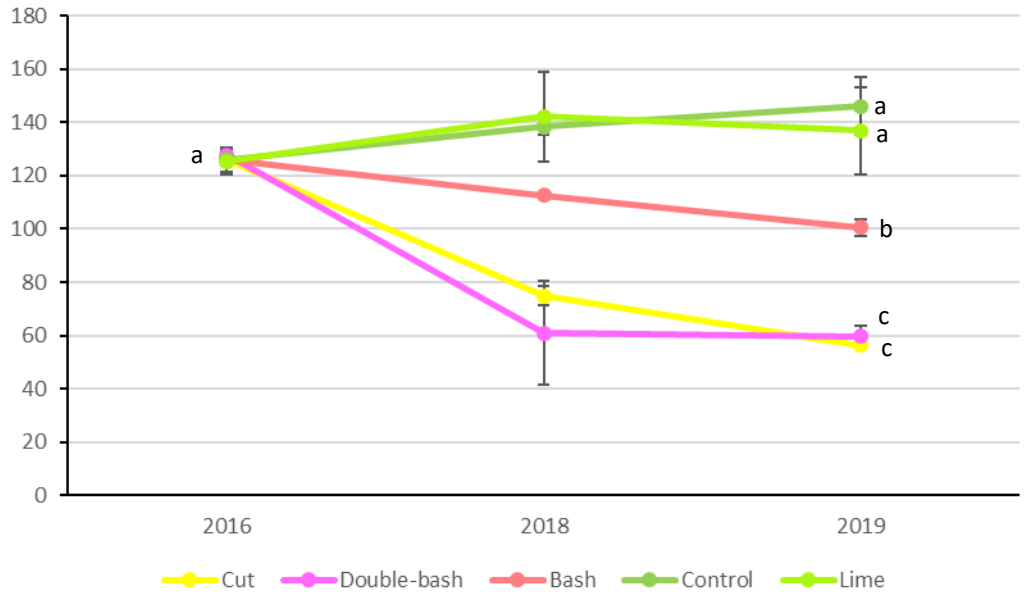


Figure 19. Mean (± standard deviation) of mean bracken frond height of tallest 10 fronds per quadrat in mechanical/liming treatment plots at Challacombe Farm, Devon, 2016, 2018-2019

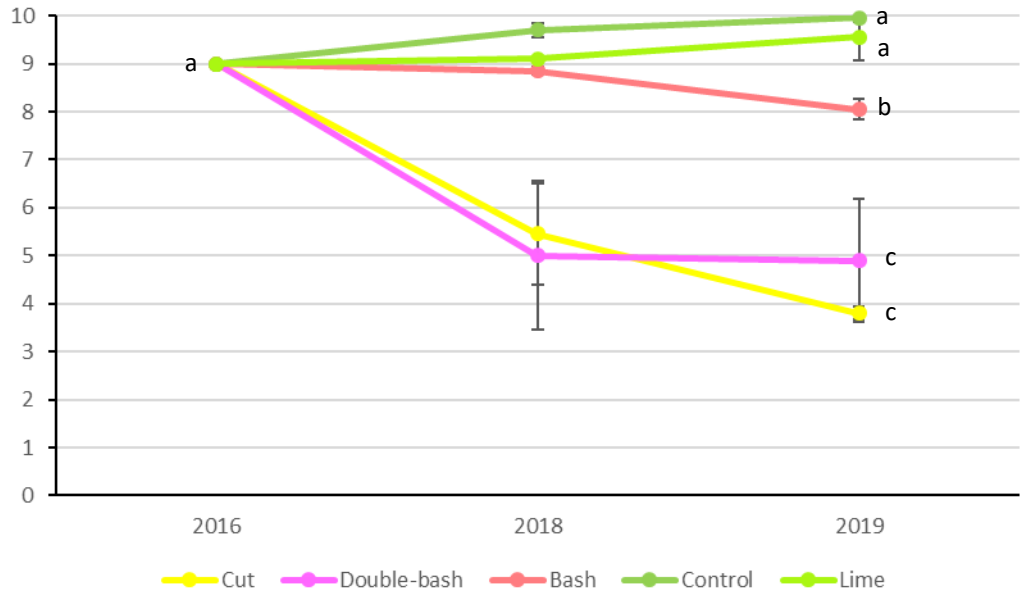


Figure 20. Mean (± standard deviation) bracken vigour score in mechanical/liming treatment plots at Challacombe Farm, Devon, 2016, 2018-2019

3.1.4 *BRACKEN VIGOUR AT CHEMICAL TREATMENT EXPERIMENTAL PLOTS, CHALLACOMBE FARM, DEVON*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

There were no significant differences in pre-treatment bracken cover in 2016 (figure 21, below). By 2019, *cover* in all treatments was significantly lower than the Control (all $P < 0.001$ except Control vs. Asulam 1N which was $P < 0.01$). In addition, the bracken *cover* in the Amidosulfuron 1N treatment was significantly lower than in the Asulam 1N and Metsulfuron 1N treatments (both $P < 0.001$) and Amidosulfuron 0.5N ($P < 0.01$).

There were no significant differences in pre-treatment bracken *shoot density* or *frond height* in 2016. By 2019, the Amidosulfuron 1N and Amidosulfuron 0.5N treatments had significantly lower *shoot densities* and *frond height* than the Control (figures 22 & 23, below (all $P < 0.001$ except *shoot density* Amidosulfuron 0.5N vs. Control, which was $P < 0.05$)).

There were no significant differences in pre-treatment bracken *vigour* in 2016. By 2019, the *vigour* scores in the all the chemical treatments were significantly lower than the Control treatment (figure 24, below (Amidosulfuron 1N $P < 0.001$, Amidosulfuron 0.5N $P < 0.01$, Asulam 1N $P < 0.05$)). Bracken *vigour* in the Amidosulfuron 1N treatment was also significantly lower than the Amidosulfuron 0.5N and Metsulfuron 1N treatments ($P < 0.05$). In addition, bracken *vigour* was significantly lower in the Amidosulfuron 1N treatment compared with Asulam 1N ($P < 0.01$).

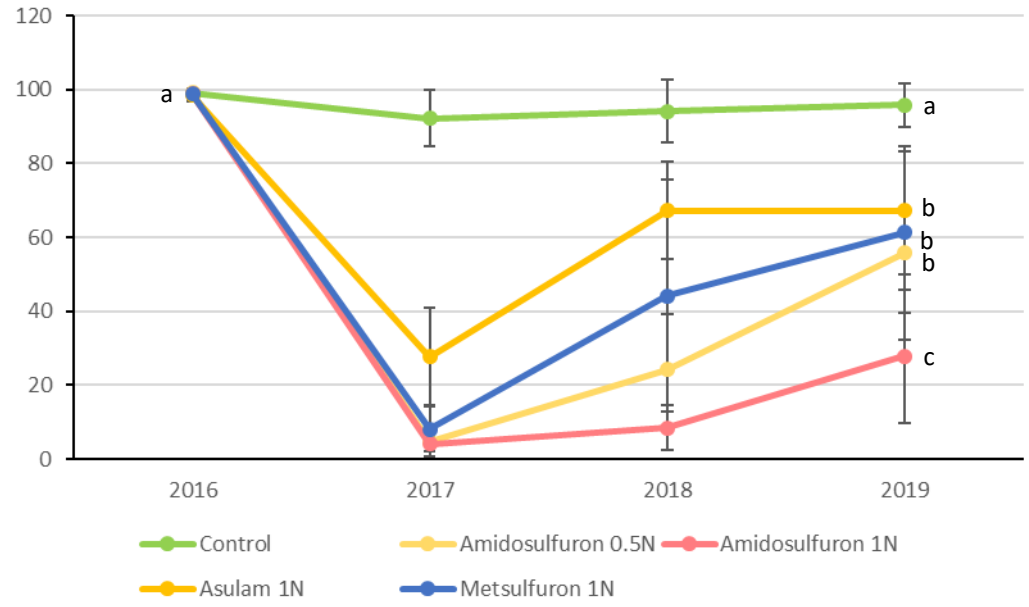


Figure 21. Mean (± standard deviation) cover (%) of bracken in chemical treatment plots at Challacombe Farm, Devon, 2016-2019

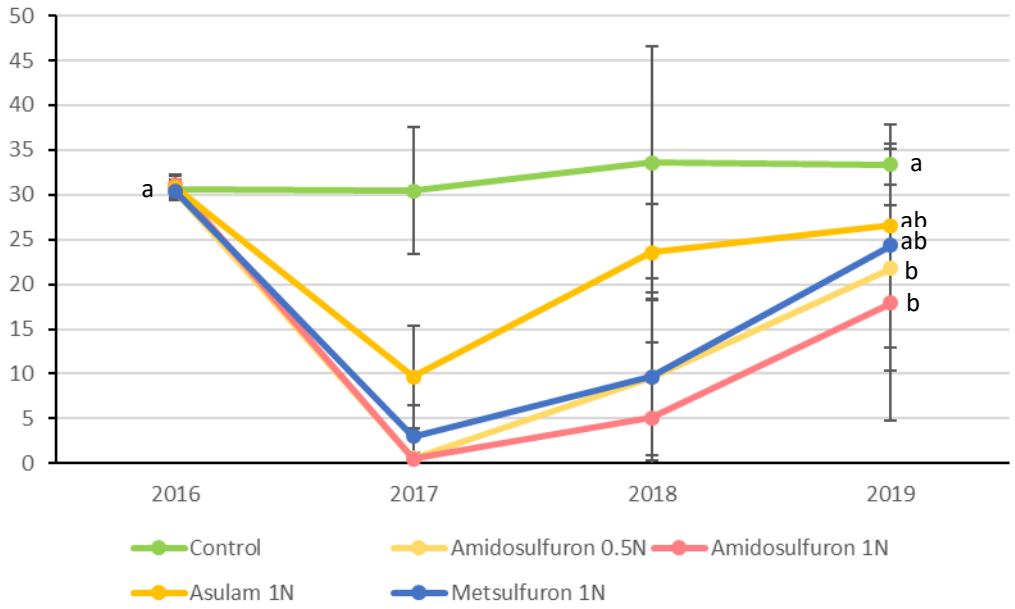


Figure 22. Mean number (± standard deviation) of living bracken shoots per m^2 in chemical treatment plots at Challacombe Farm, Devon, 2016-2019

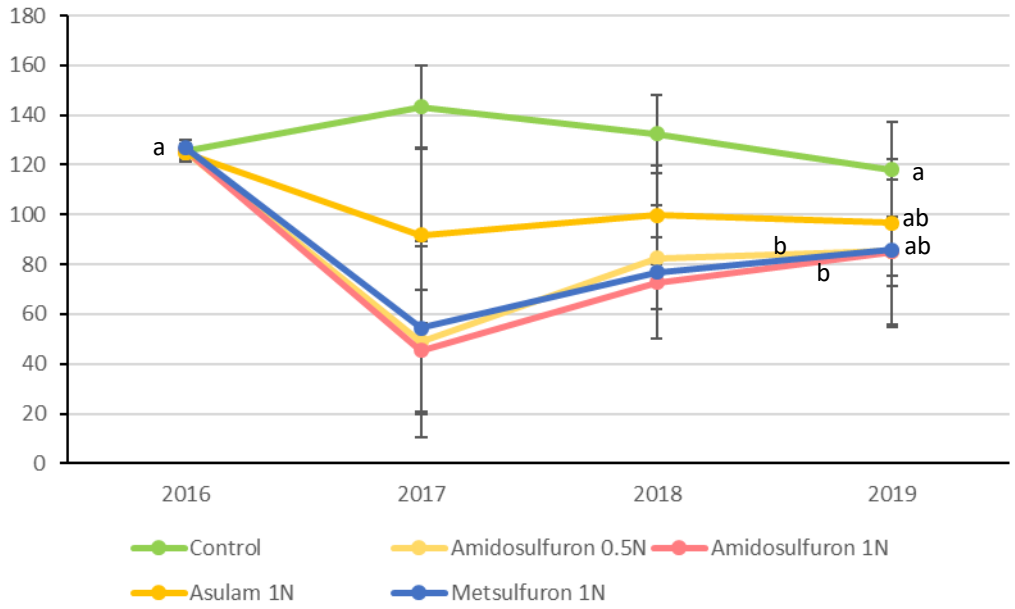


Figure 23. Mean (± standard deviation) of mean bracken frond height of tallest 5 fronds per plot in chemical treatment plots at Challacombe Farm, Devon, 2016-2019

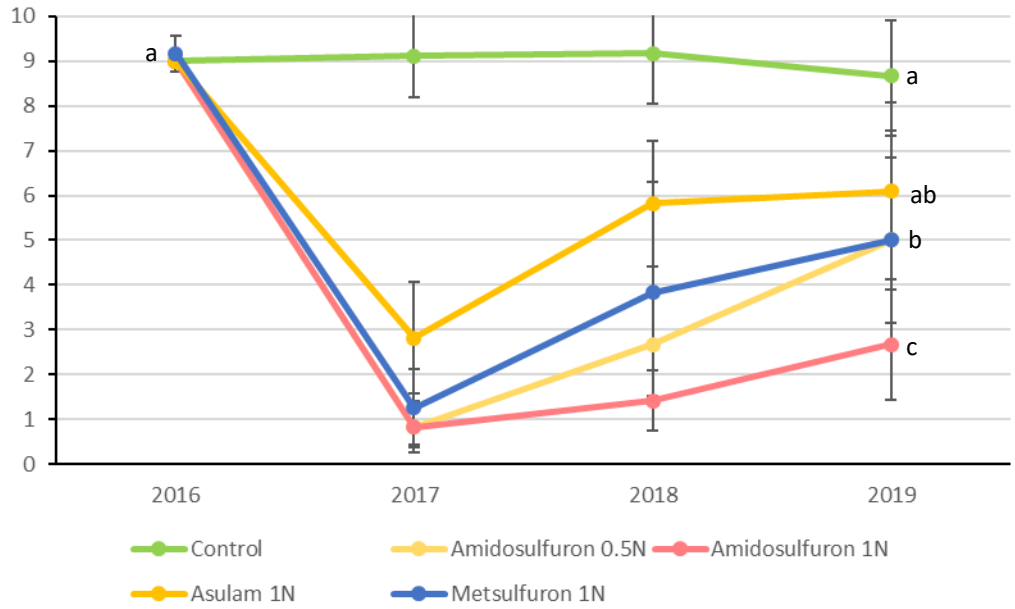


Figure 24. Mean (± standard deviation) bracken vigour score in chemical treatment plots at Challacombe Farm, Devon, 2016-2019

3.1.5 *BRACKEN VIGOUR AT CHEMICAL TREATMENT EXPERIMENTAL PLOTS, FAWDON FARM, NORTHUMBERLAND*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

There were no significant differences in bracken *cover*, *shoot density*, *frond height* and bracken *vigour* scores between the treatments in the baseline year 2016.

By 2019, bracken *cover* and was significantly lower than the Control in all treatments (figure 25, below (all $P < 0.01$, except Control vs. Metsulfuron 1N which was $P < 0.001$)). *Shoot density* was also significantly lower than the Control in all treatments (figure 26, below (all $P < 0.001$, except Control vs. Asulam 1N which was $P < 0.05$)).

In 2019, *frond height* was significantly lower than the Control, for the Amidosulfuron 1N and Amidosulfuron 0.5N and Metsulfuron 1N treatments ($P < 0.05$), but not the Asulam 1N treatment (figure 27, below).

Bracken *vigour* score (figure 28, below) was significantly lower than the Control in the Amidosulfuron 1N ($P < 0.05$), Amidosulfuron 0.5N ($P < 0.01$) and Metsulfuron 1N ($P < 0.01$) treatments.

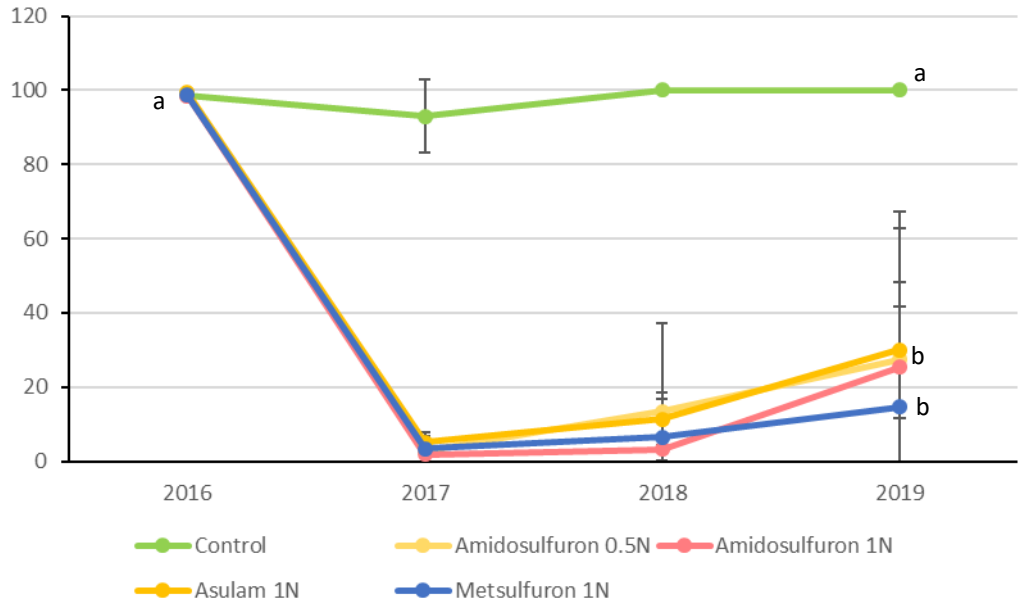


Figure 25. Mean (± standard deviation) cover (%) of bracken in chemical treatment plots at Fawdon Farm, Northumberland, 2016-2019

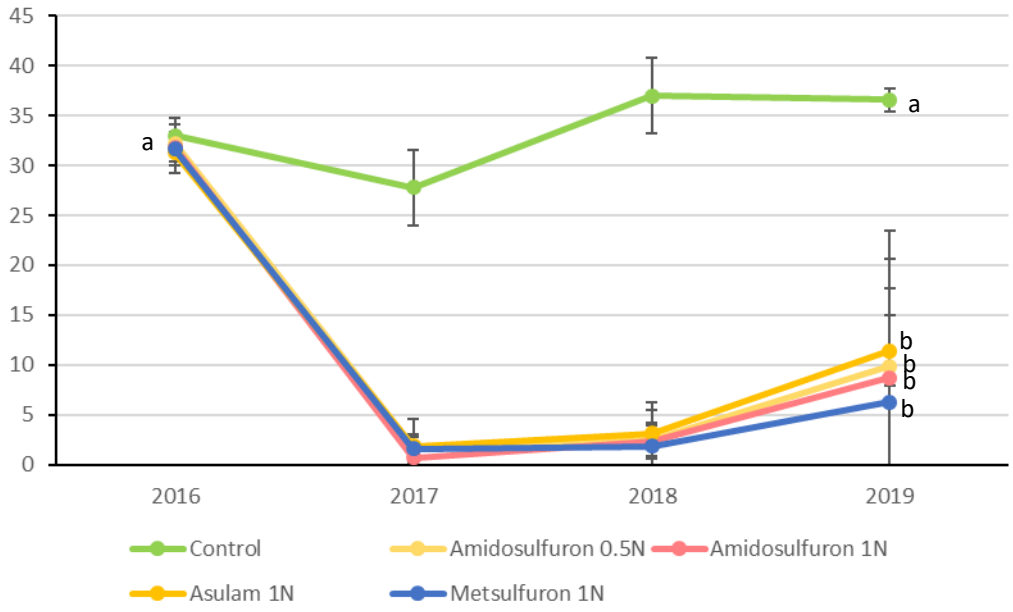


Figure 26. Mean number (± standard deviation) of living bracken shoots per m^2 in chemical treatment plots at Fawdon Farm, Northumberland, 2016-2019

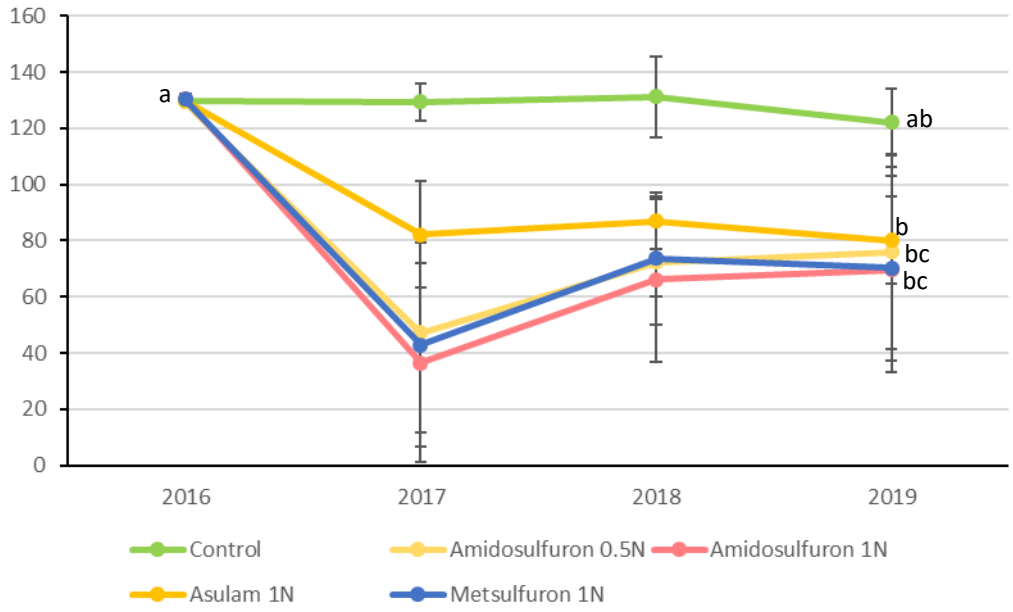


Figure 27. Mean (± standard deviation) of mean bracken frond height of tallest 10 fronds per plot in chemical treatment plots at Fawdon Farm, Northumberland, 2016-2019

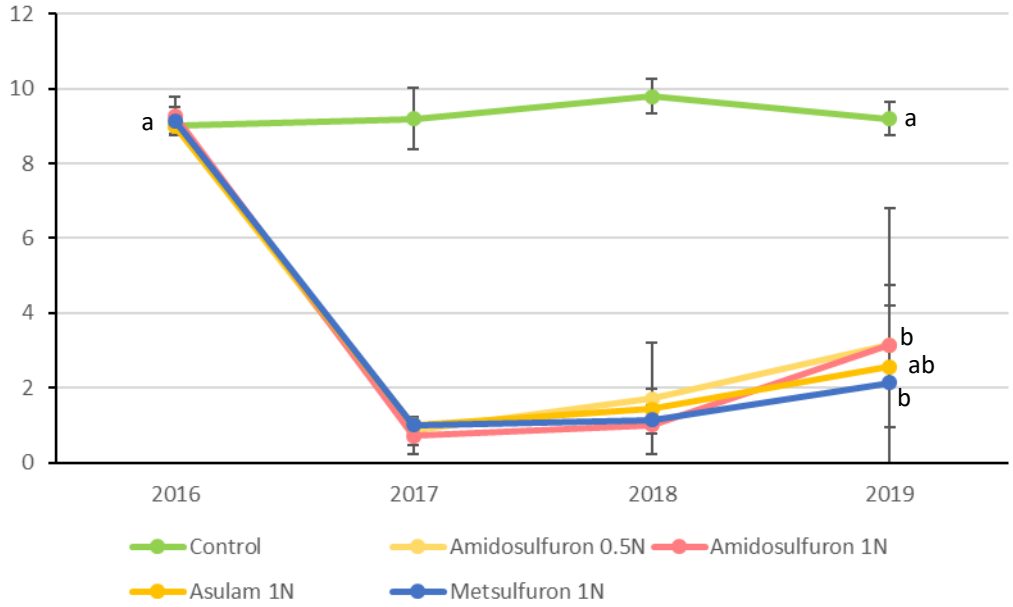


Figure 28. Mean (± standard deviation) bracken vigour score in chemical treatment plots at Fawdon Farm, Northumberland, 2016-2019

3.2 VEGETATION DYNAMICS AT INGRAM, FAWDON AND CHALLACOMBE FARMS

3.2.1 *UNDERSTOREY IN EXPERIMENTAL PLOTS ESTABLISHED IN 2011 AT INGRAM FARM, NORTHUMBERLAND*

This section presents findings from data collected by Archaeological Research Services Ltd in 2011-14 and Ketmar in 2016-19.

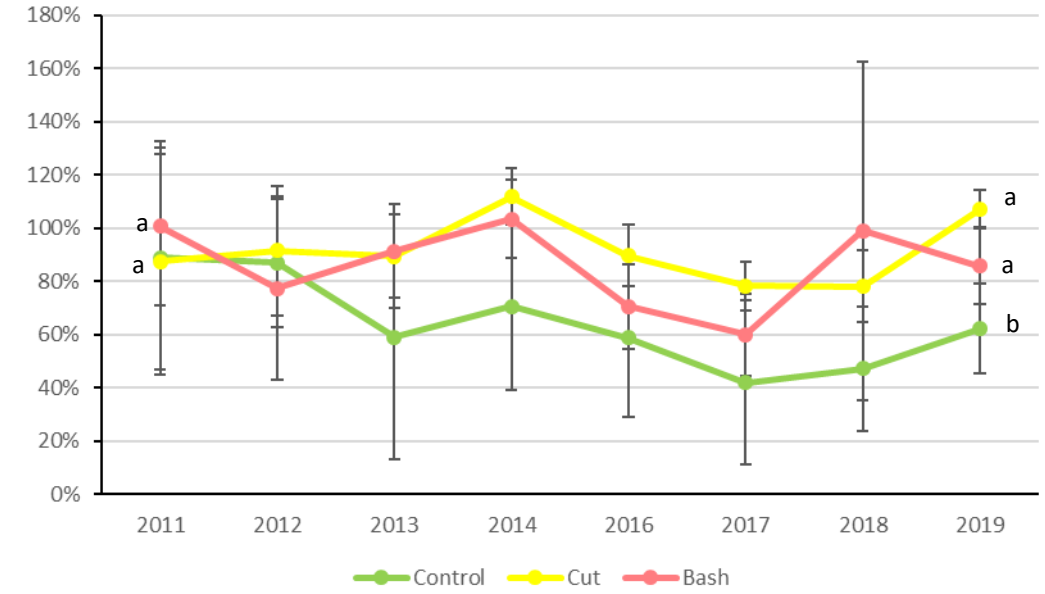
The understorey cover and species richness in plots established in 2011 are shown in figures 29 & 30, below. Data from the newly established plots are shown in the figures comparing plots in 2019, but are not shown in the figures of time-series data in this section. The time-series data for the plots established in 2016 can be found in section 3.2.2, below.

In 2011 there were no significant differences in understorey cover (% cover of vegetation under the bracken layer) or species richness between mechanical treatments.

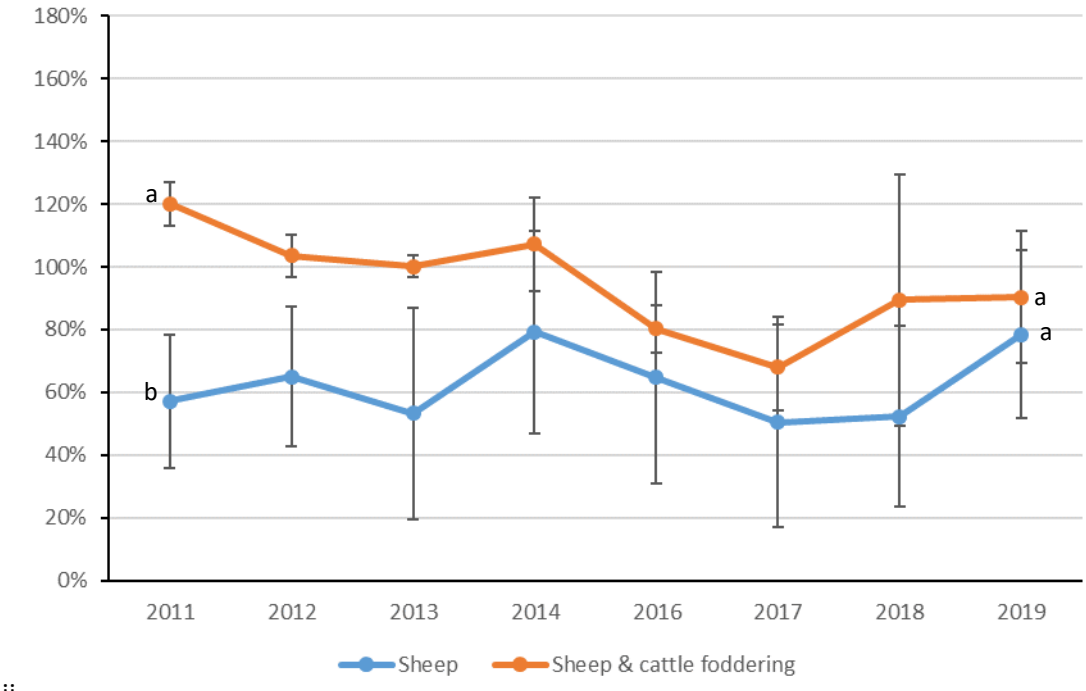
In 2019 understorey cover was significantly higher in the Cut ($P < 0.001$) and Bash ($P < 0.01$) treatments compared with the Control (figure 29i, below). Species richness in 2019 was also significantly higher in the Cut and treatment compared with the Control (figure 30i, below ($P < 0.05$)).

In 2011, prior to any treatments, understorey cover (figure 29ii, below) and species richness (figure 30ii, below) were both significantly higher in the cattle winter foddering treatment (Wether Hill) compared with no cattle foddering (Ewe Hill, $P < 0.001$). In 2019 species richness was still significantly higher ($P < 0.001$) in the cattle foddering treatment, but understorey cover was no longer significantly higher.

Comparison of the *Control* plots on Wether Hill vs. Ewe Hill provided a basis for assessing the treatment effect of winter cattle foddering between treatments, although site-specific differences in vegetation are likely to have been important. Species richness in the Control plots was significantly higher in the cattle winter foddering treatment at the start *and* end of the experiment (both $P < 0.05$). Conversely, understorey cover was initially significantly higher in the Control plots receiving cattle winter foddering ($P < 0.01$), but there was no significant difference by the end of the experiment.

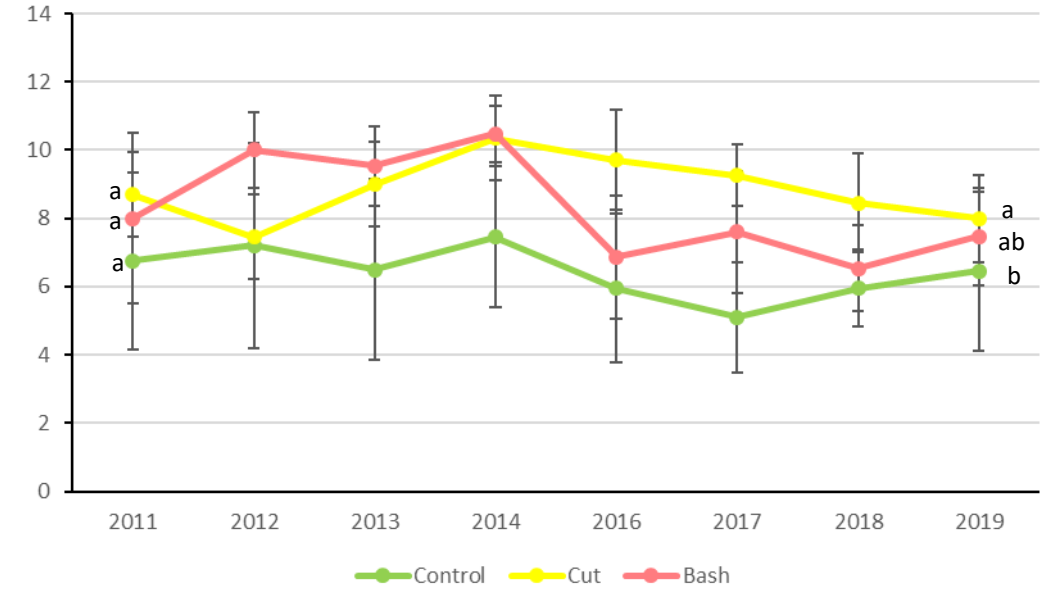


i

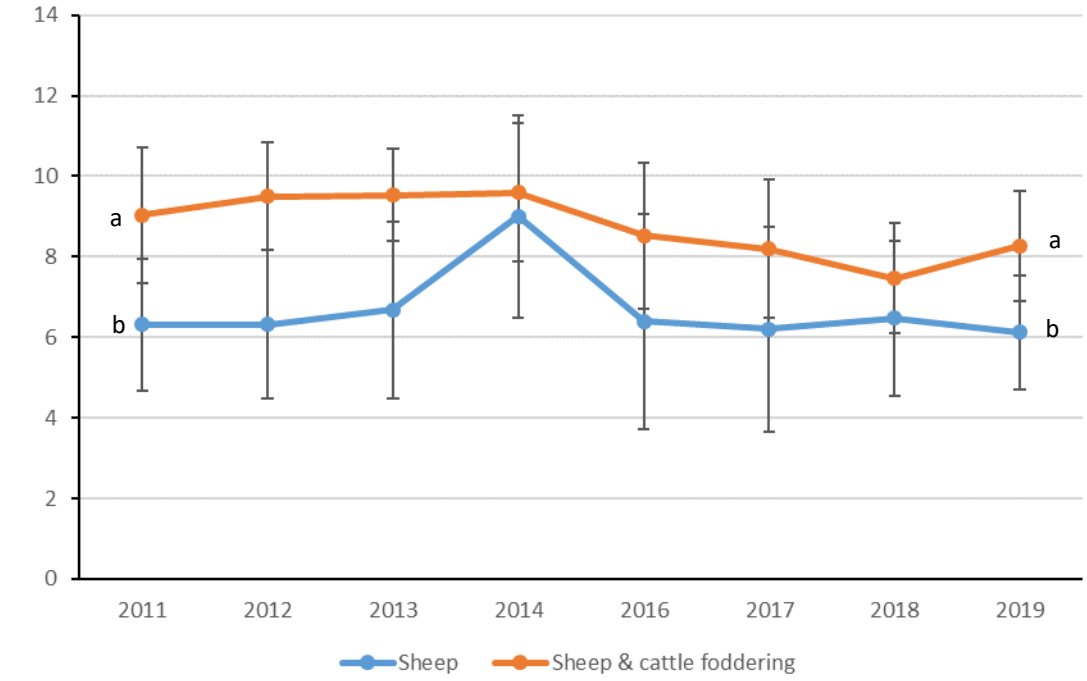


ii

Figure 29. Mean (± standard deviation) understorey cover (%) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016



i



ii

Figure 30. Mean (± standard deviation) species richness at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016

3.2.2 *UNDERSTOREY IN NEW EXPERIMENTAL PLOTS ESTABLISHED IN 2016 AT INGRAM FARM, NORTHUMBERLAND*

This section presents findings from data collected by Ketmar in 2016-19.

The understorey cover and species richness in the new plots on Ewe Hill, Ingram Farm (plots 3, 4 & 8) are shown below in figures 31 & 32 with the mean figures for the Control plots on Ewe Hill.

When the new plots were established in 2016, there were no significant differences in understorey cover or species richness between either of the designated treatments and the Control. At the end of the experiment in 2019, understorey cover was significantly higher in the Bash and Double-bash treatments compared with the Control (figure 31, below ($P < 0.001$)). Species richness was significantly higher in the Bash treatment compared with the Control (figure 32, below ($P < 0.001$)).

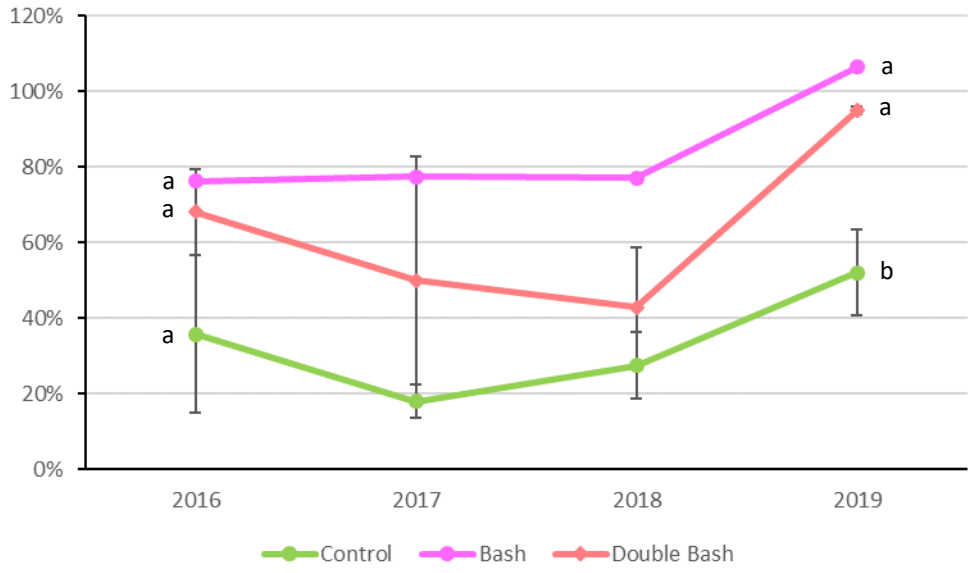


Figure 31. Mean (± standard deviation) understorey cover (%) in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

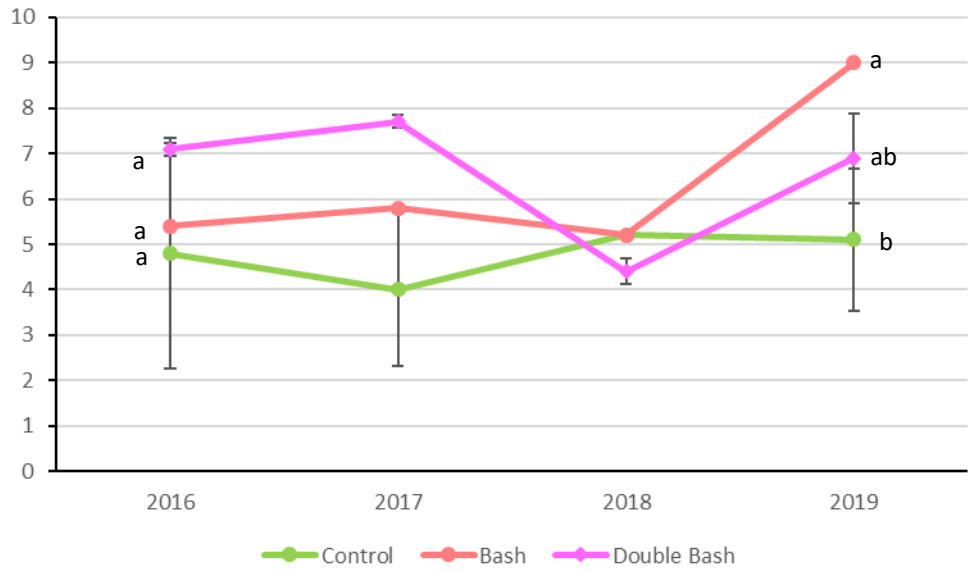


Figure 32. Mean (± standard deviation) species richness in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm and mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

3.2.3 *UNDERSTOREY IN EXPERIMENTAL PLOTS AT CHALLACOMBE FARM, DEVON; PHYSICAL & LIMING TREATMENTS*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

Summary measures of vegetation data from the quadrats recorded in the physical and liming treatment plots are shown in figures 33 & 34, below.

At the time when the plots were established in 2016, there were two pairs of treatments with significant differences in understorey cover; Bash vs. Control ($P < 0.01$, $P < 0.05$, respectively) and Bash vs. Liming treatment ($P < 0.001$, $P < 0.01$ respectively). By 2019, this had been reversed, and all mechanical treatments had significantly higher understorey cover than the Control and the Liming treatment (figure 33, below ($P < 0.001$)).

In 2016, species richness was significantly higher in the Double-bash treatment than all other treatments ($P < 0.01$) and Control ($P < 0.001$). This had been reversed by 2019, with species richness significantly higher in the mechanical treatments compared with the Liming treatment and Control (figure 34, below (all $P < 0.001$ except Liming vs. Bash and Liming vs. Cut treatments where $P < 0.01$)).

Figure 33. Mean (± standard deviation) understorey cover (%) 2016-2019 at Challacombe Farm, Devon, split by mechanical & liming treatments

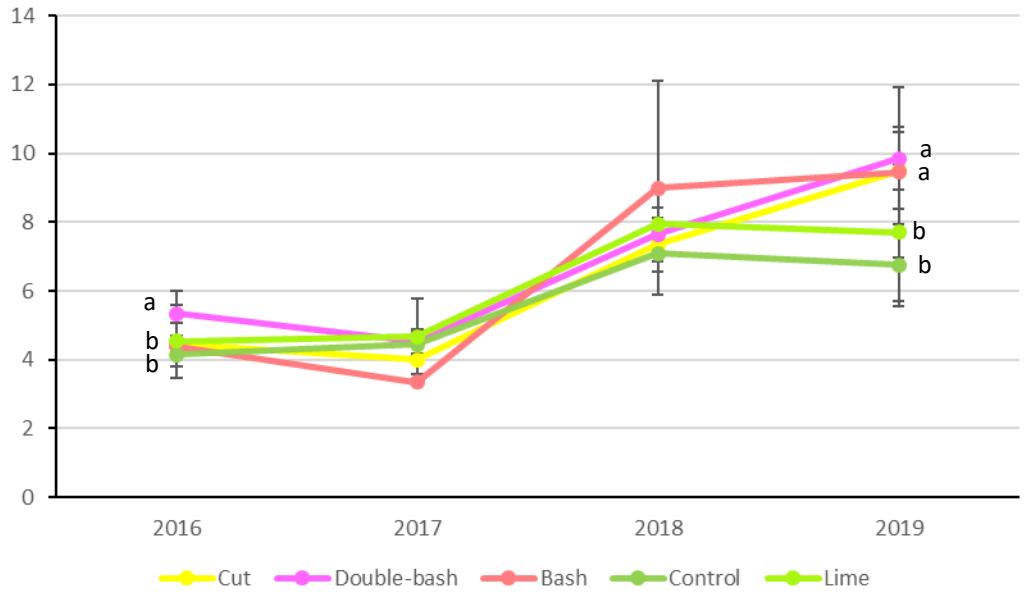


Figure 34. Mean (± standard deviation) species richness 2016-2019 at Challacombe Farm, Devon, split by mechanical & liming treatments

3.2.4 *UNDERSTOREY IN EXPERIMENTAL PLOTS AT CHALLACOMBE FARM, DEVON; CHEMICAL TREATMENTS*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

There were no significant differences between assigned treatments, for understorey cover, species richness or litter cover in 2016. In 2017 there was a noticeable dip in species richness, more marked than that seen in the physical and liming plots (figure 34, above). Anecdotally, this pattern was observed at other sites monitored by R & D Applied biology in 2017 as part of their National Chemical Bracken Control Trials, but not at the other two sites which form the basis of this study; Ingram Farm and Fawdon Farm, Northumberland.

By 2019, all chemical treatments had significantly greater understorey cover than the Control (figures 35, below ($P < 0.001$)). However, in 2019 there were no significant differences in species richness between treatments (figures 36, below).

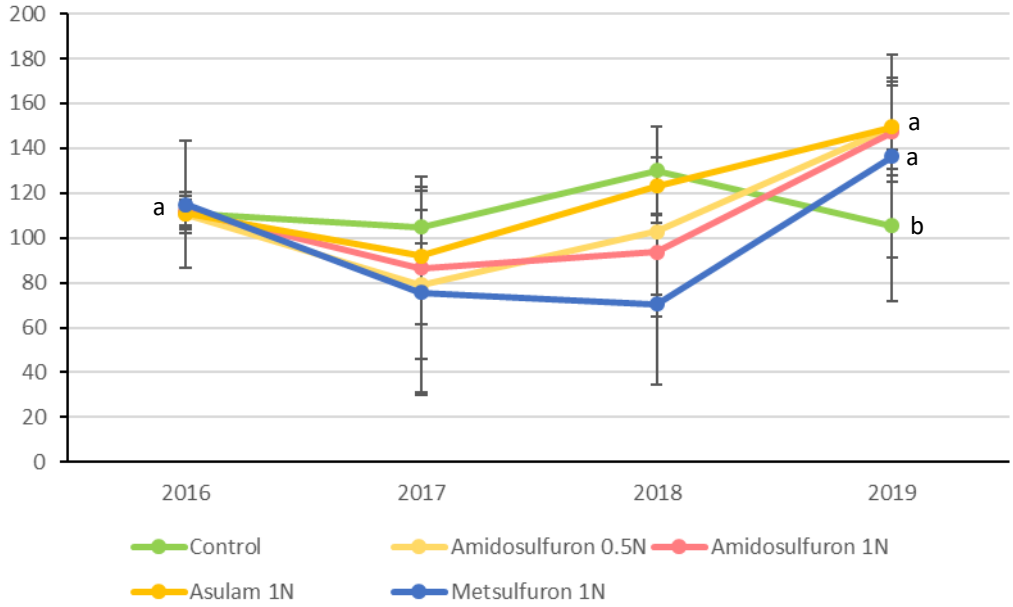


Figure 35. Mean (± standard deviation) understorey cover (%) 2016-2019 at Challacombe Farm, Devon, split by chemical treatments

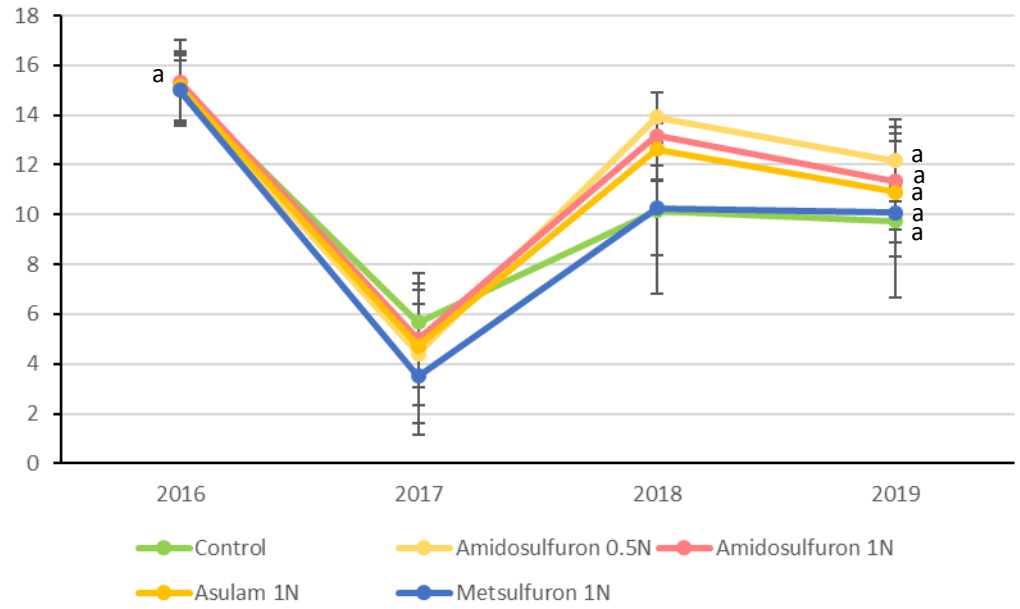


Figure 36. Mean (± standard deviation) species richness 2016-2019 at Challacombe Farm, Devon, split by chemical treatments

3.2.5 *UNDERSTOREY IN EXPERIMENTAL PLOTS AT FAWDON FARM, NORTHUMBERLAND*

This section presents the findings from data collected by R & D Applied Biology in 2016-17, and by the same recorder from R & D Applied Biology in 2018-19 on behalf of Ketmar.

In 2016 there were no significant differences in understorey cover or species richness between the combined plots assigned for each treatment. By 2019 there were still no significant differences in understorey cover and species richness between treatments (figures 37 & 38, below).

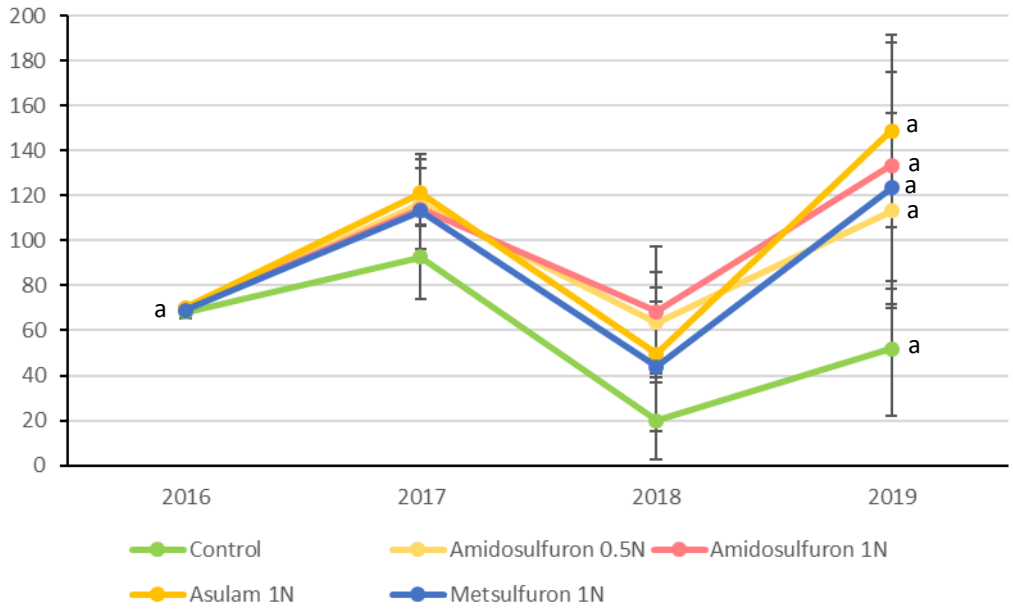


Figure 37. Mean (± standard deviation) understorey cover (%) 2016-2019 at Fawdon Farm, Northumberland, split by chemical treatments

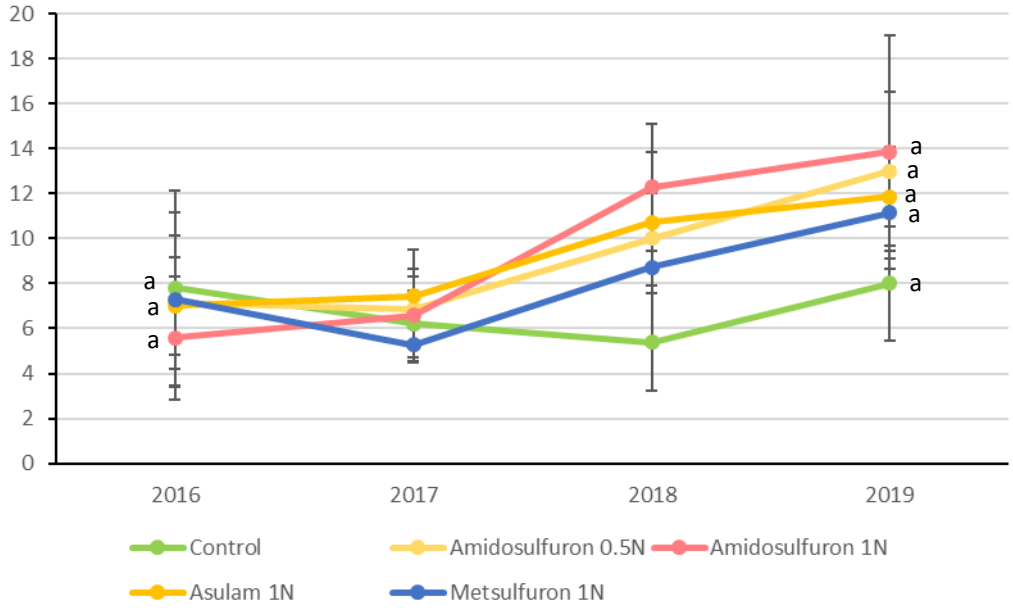
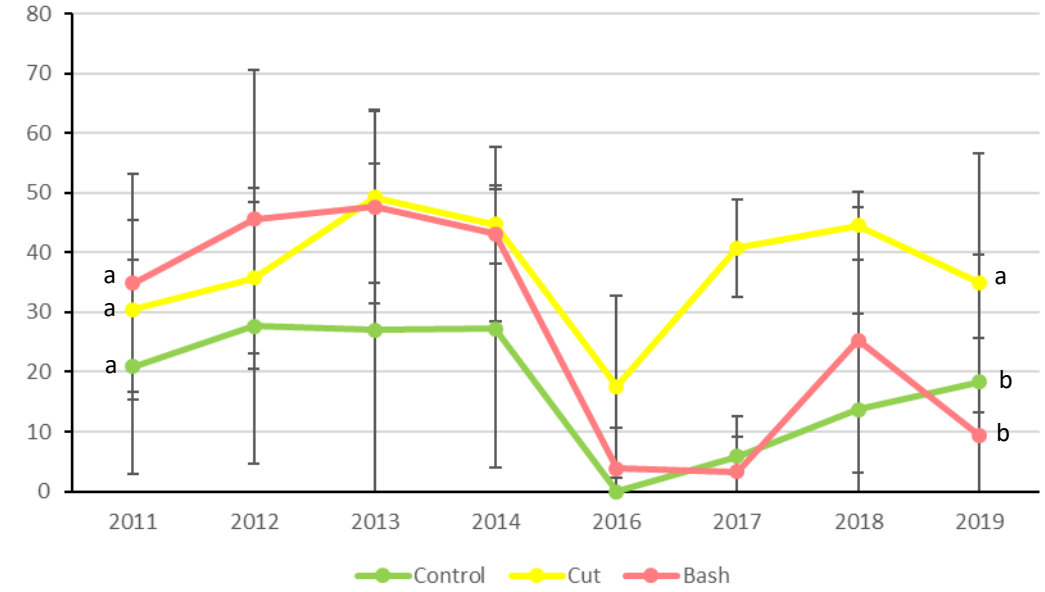


Figure 38. Mean (± standard deviation) species richness 2016-2019 at Fawdon Farm, Northumberland, split by chemical treatments

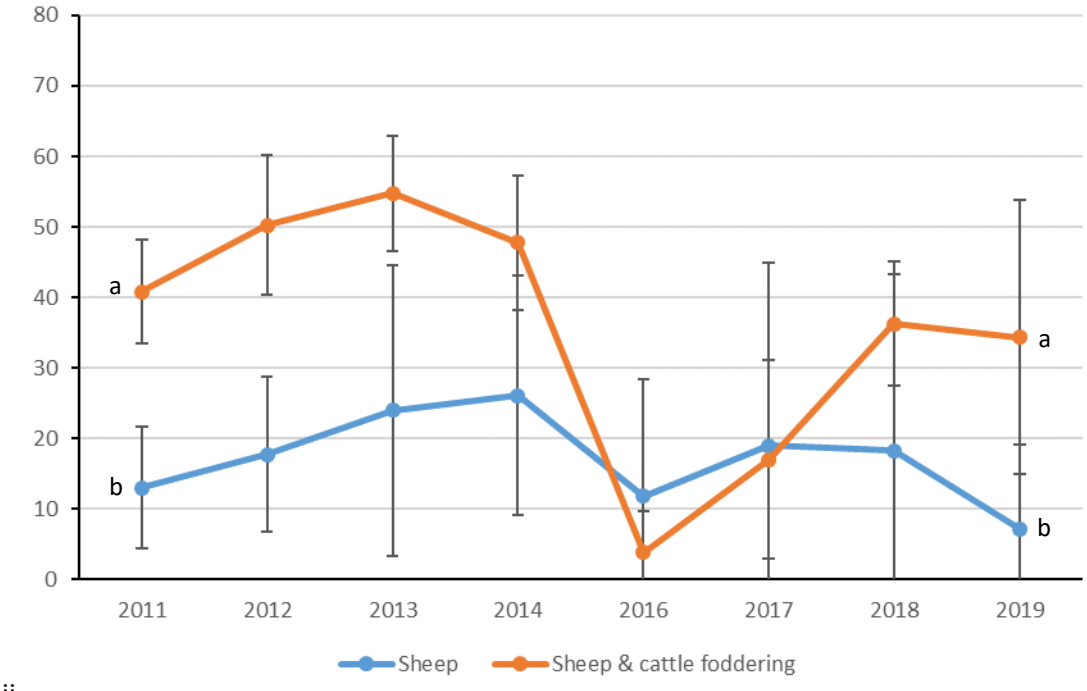
3.2.6 CHANGES IN NVC SCORES OVER TIME *IN EXPERIMENTAL PLOTS ESTABLISHED IN 2011 AT INGRAM FARM, NORTHUMBERLAND*

Figures 39-42 below, show the changes in Tablefit-derived matches to NVC U4b, U20a, U20b and U20c communities, split by treatment. With the exception of the 2011 and 2012 U20c scores, there was a high level of variation in matches to any given community. Despite this, there were some discernible trends after nine years. By 2019, U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community, figure 41i, below) and U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community, figure 42i, below) saw a significant reduction in the Cut treatment compared with the Bash treatment and Control by 2019.

There was a corresponding significant increase in the Cut treatment match to acid grassland community U4b (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community, figure 39i, below), which was not observed in the Bash treatment or Control.

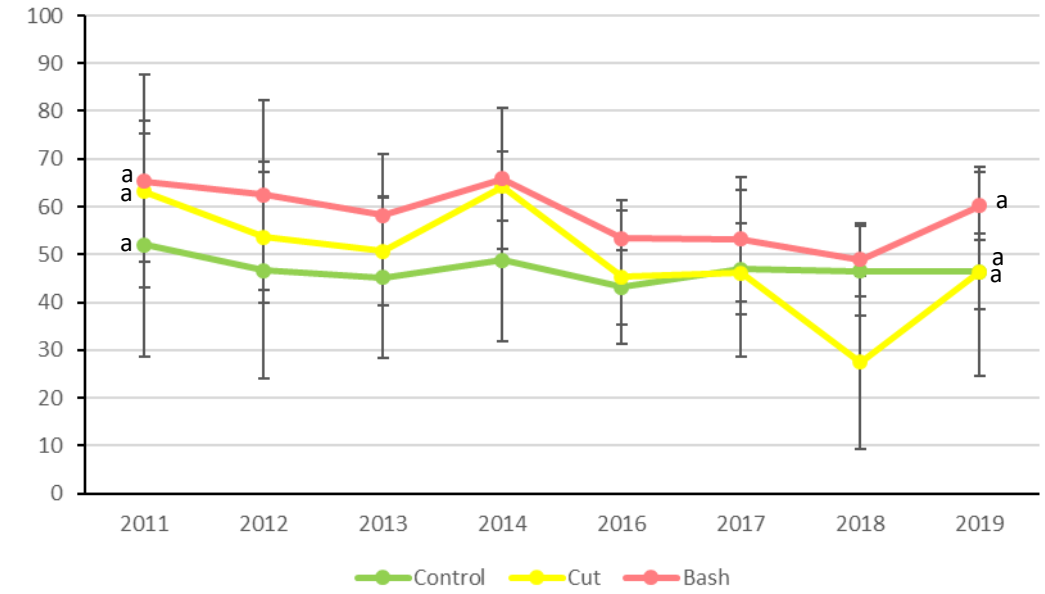


i

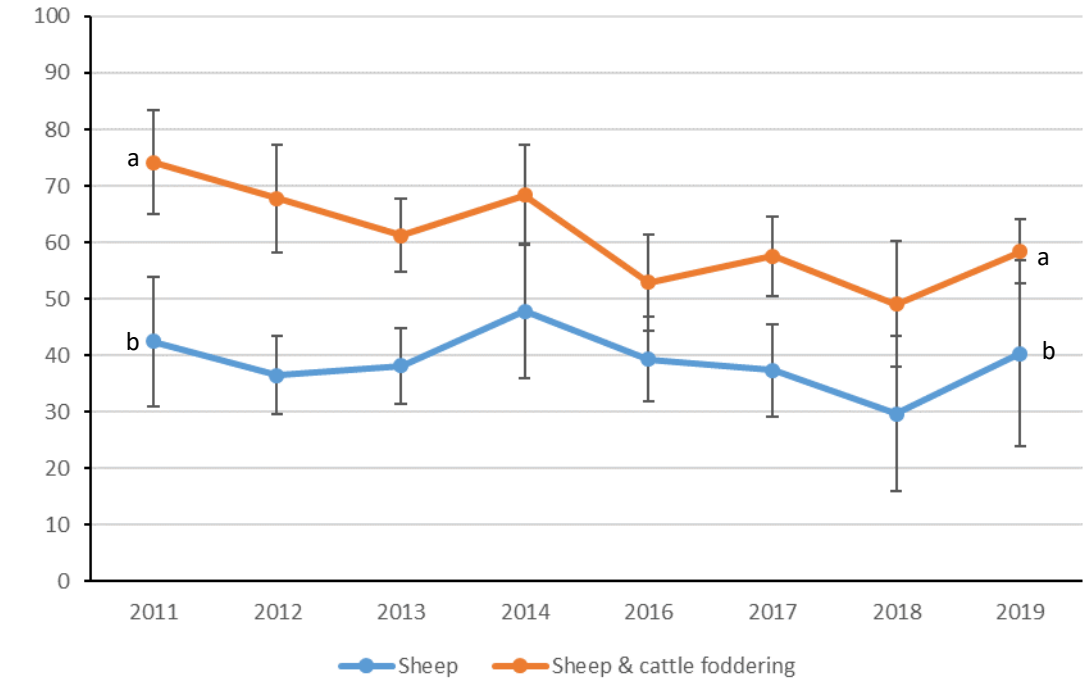


ii

Figure 39. Mean (± standard deviation) NVC U4b (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community) score 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

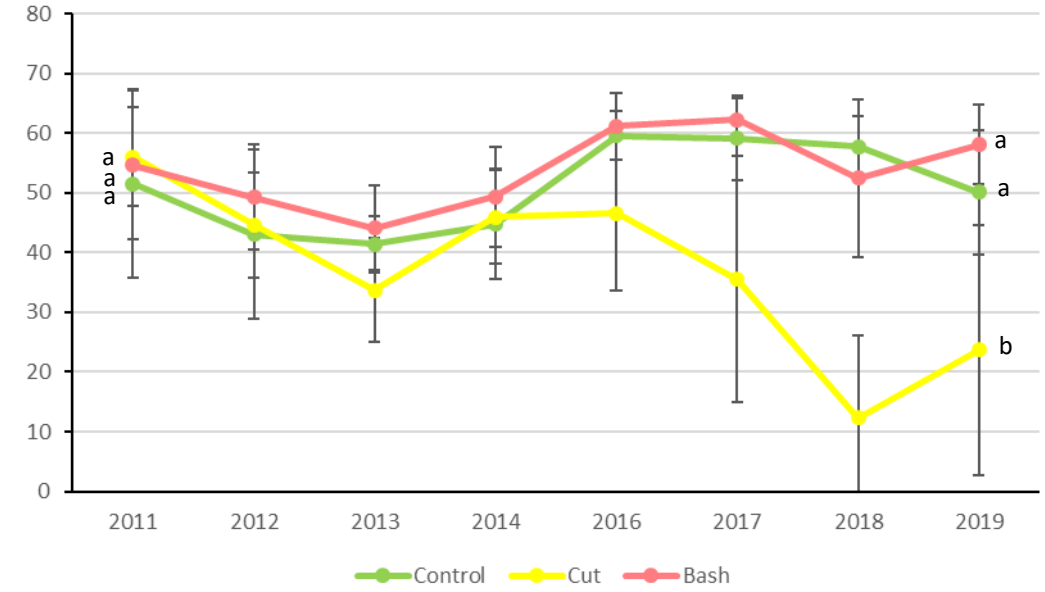


i

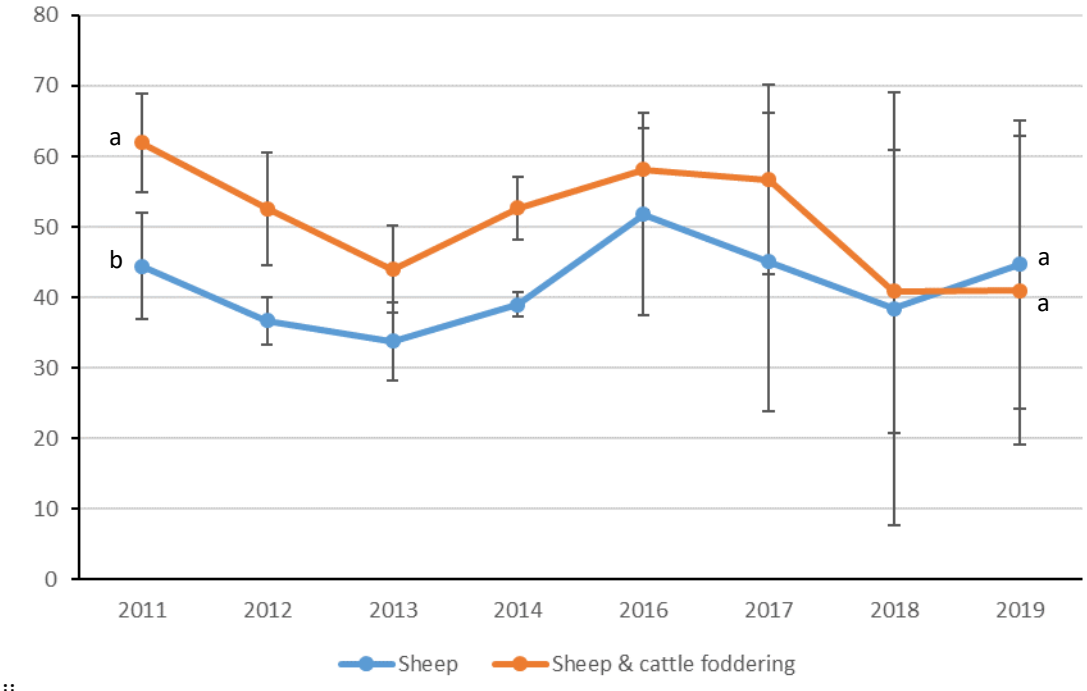


ii

Figure 40. Mean (± standard deviation) NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) score 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

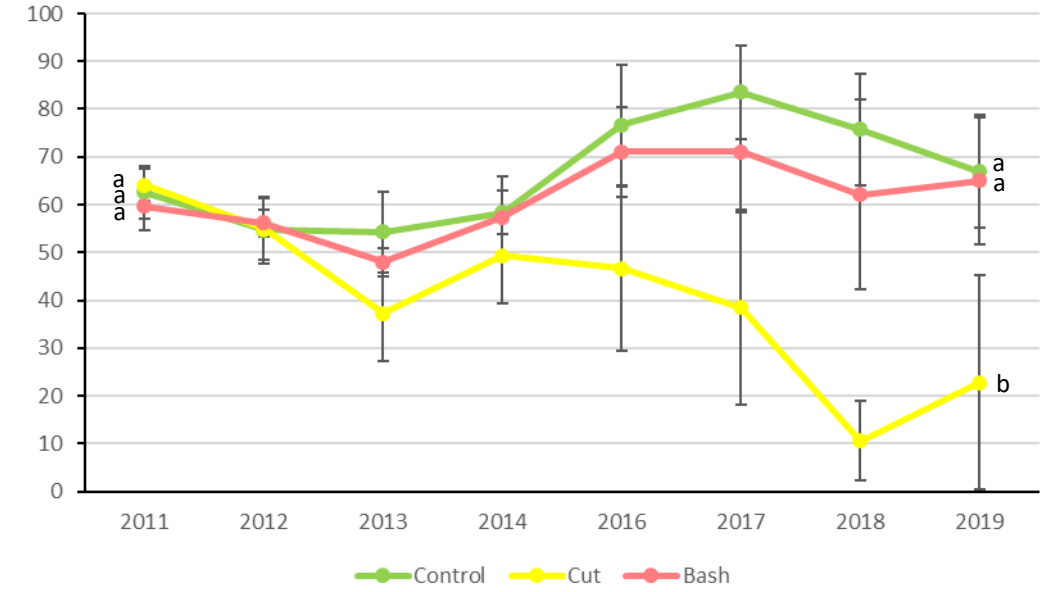


i

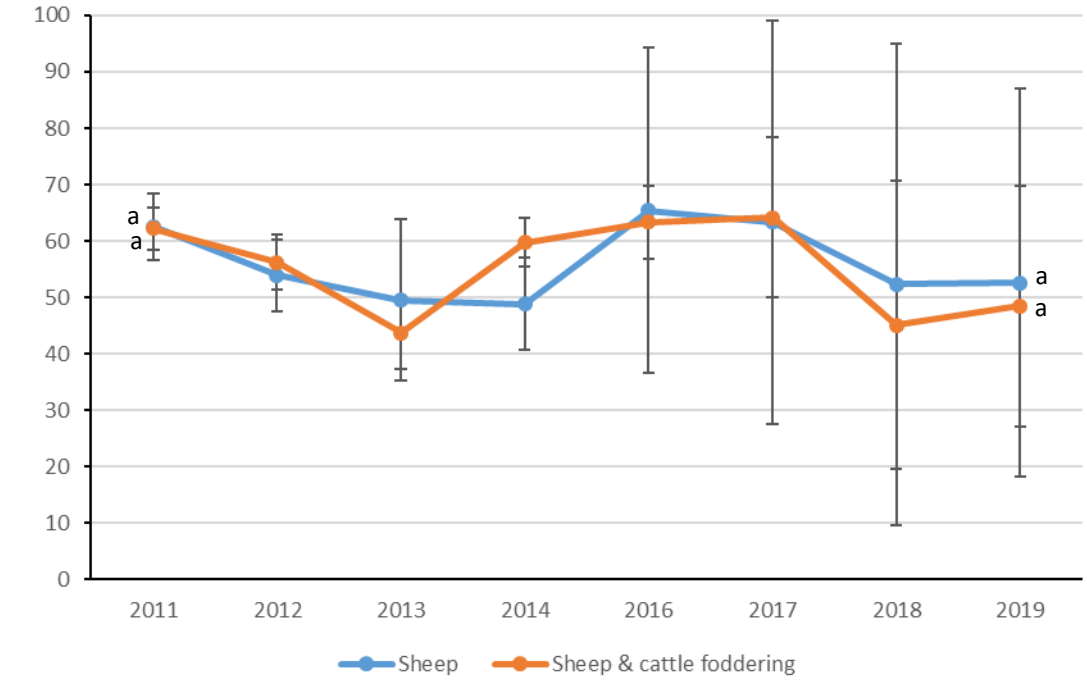


ii

Figure 41. Mean (± standard deviation) NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) score 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor



i



ii

Figure 42. Mean (± standard deviation) NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) score 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

3.2.7 CHANGES IN NVC SCORES OVER TIME *IN NEW EXPERIMENTAL PLOTS ESTABLISHED IN 2016 AT INGRAM FARM, NORTHUMBERLAND*

Figures 43-45 below, show the changes in Tablefit-derived matches to NVC U20a, U20b and U20c communities in the plots established in 2016 plus Control plots on Ewe Hill, Ingram Farm, split by treatment.

From 2016-2019, the best matches were to U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community, figure 45, below). However, at the start and end of the experiment there were no significant differences in NVC community scores between treatments for any of the communities, and none of the treatments showed a transition to acid grassland community U4b ((*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community).

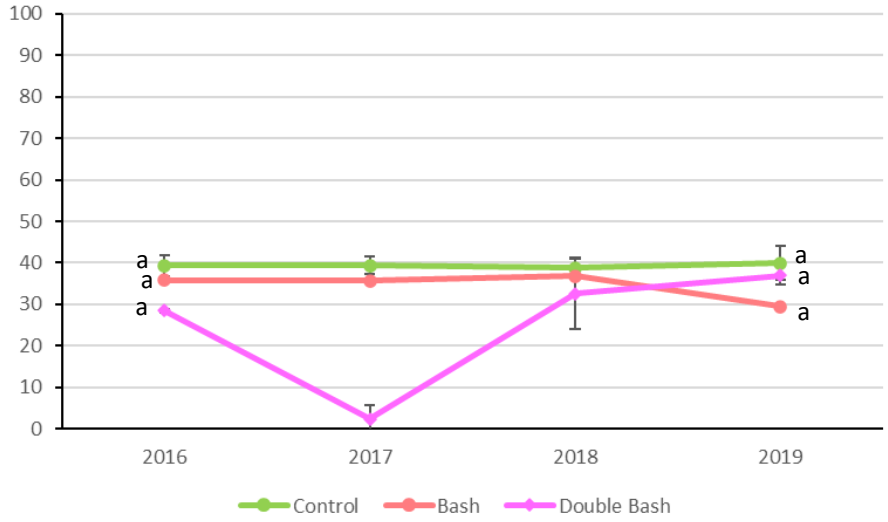


Figure 43. Mean (± standard deviation) NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) score 2016-2019, by mechanical treatment. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

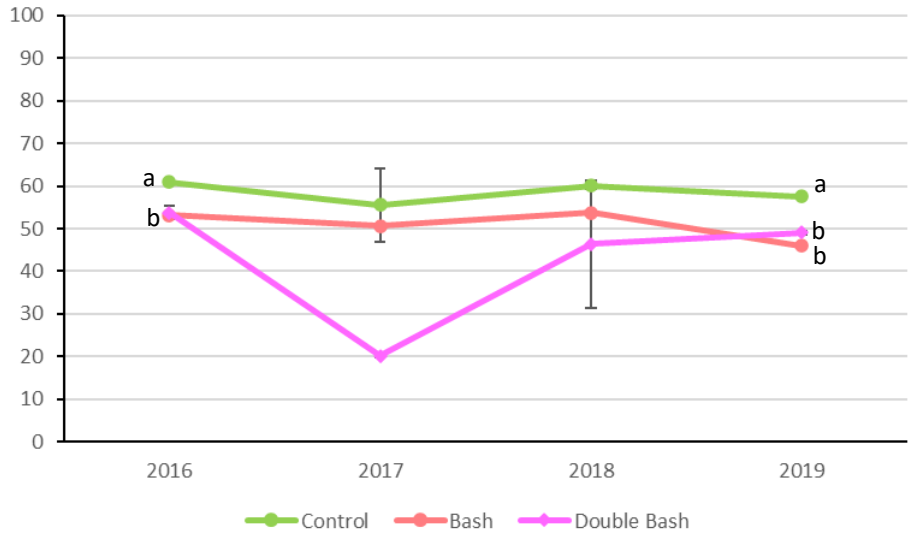


Figure 44. Mean (± standard deviation) NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) score 2016-2019, by mechanical treatment. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

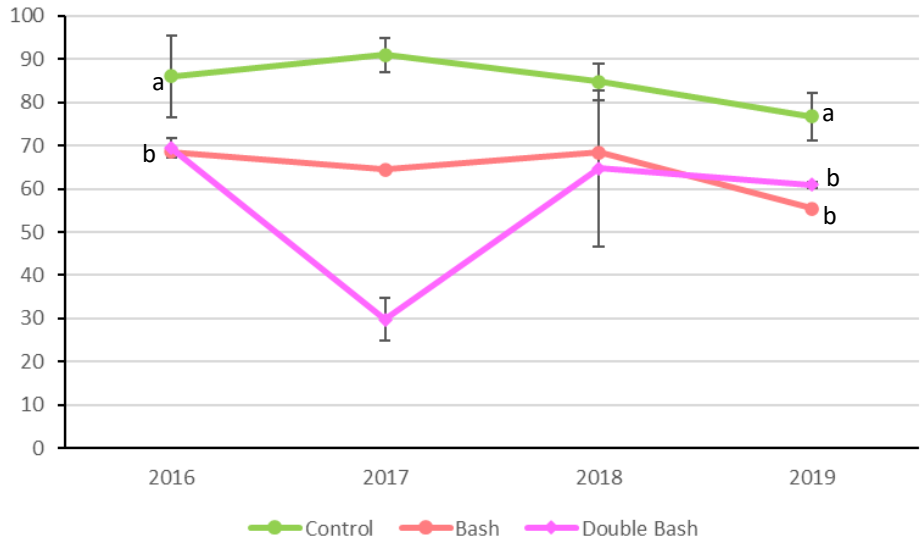


Figure 45. Mean (± standard deviation) NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) score 2016-2019, by mechanical treatment. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

3.2.8 CHANGES IN NVC SCORES OVER TIME AT CHALLACOMBE FARM, DEVON, BY PHYSICAL/LIMING TREATMENTS

Figures 46-50 below, show the changes in matches to NVC U4, U20, U20a, U20b and U20c communities, split by treatment.

In 2016 all plots scored highest, as *very good* matches to U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community, figure 49, below), although the score for the scores in plots designated for Cut and Double-bash treatments were significantly lower than the Control. By 2019, the Cut, Double-bash and Bash treatments were significantly lower than the Control and Liming treatment.

In 2016 none of the treatments' plot summary vegetation composition matched to U4 (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland, figure 50, below), whereas in 2019 the Control, Cut and Double-bash plots scored as very poor and poor matches to U4.

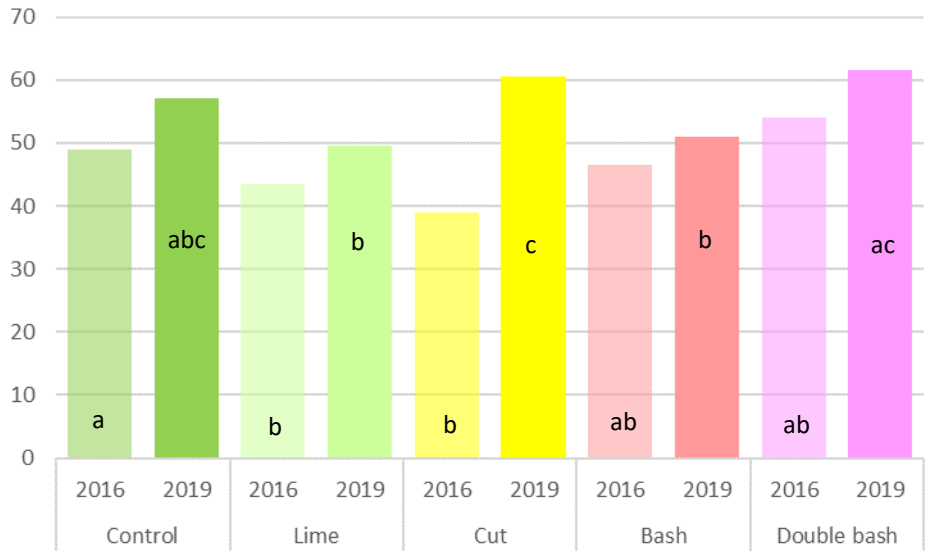


Figure 46. Mean (of plots) NVC U20 (*Pteridium aquilinum - Galium saxatile* community) score 2016 & 2019, by mechanical/liming treatment at Challacombe Farm, Devon. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

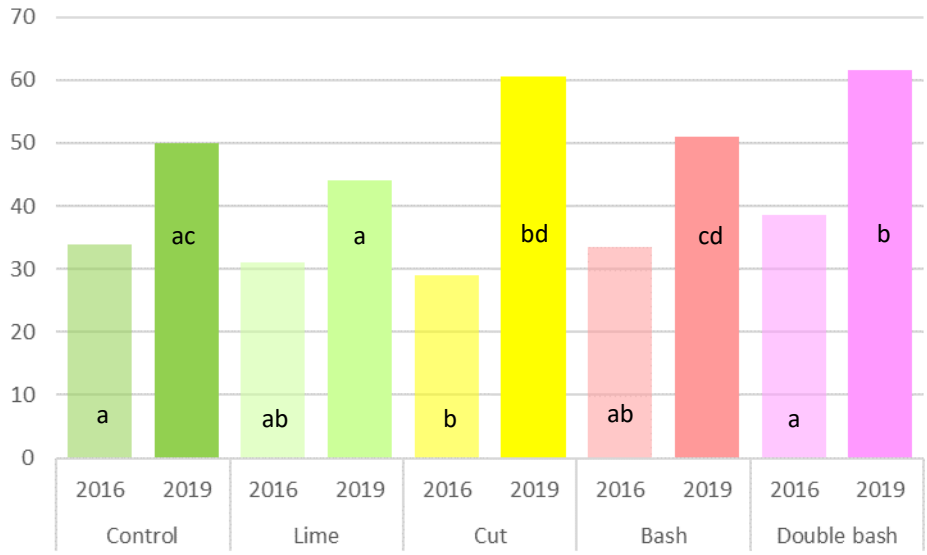


Figure 47. Mean (of plots) NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) score 2016 & 2019, by mechanical/liming treatment at Challacombe Farm, Devon. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

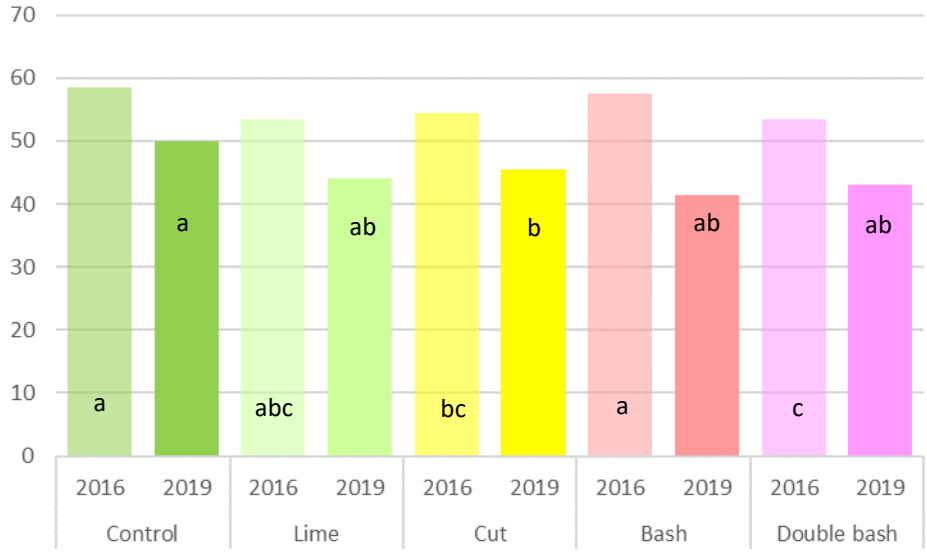


Figure 48. Mean (of plots) NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) score 2016 & 2019, by mechanical/liming treatment at Challacombe Farm, Devon. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

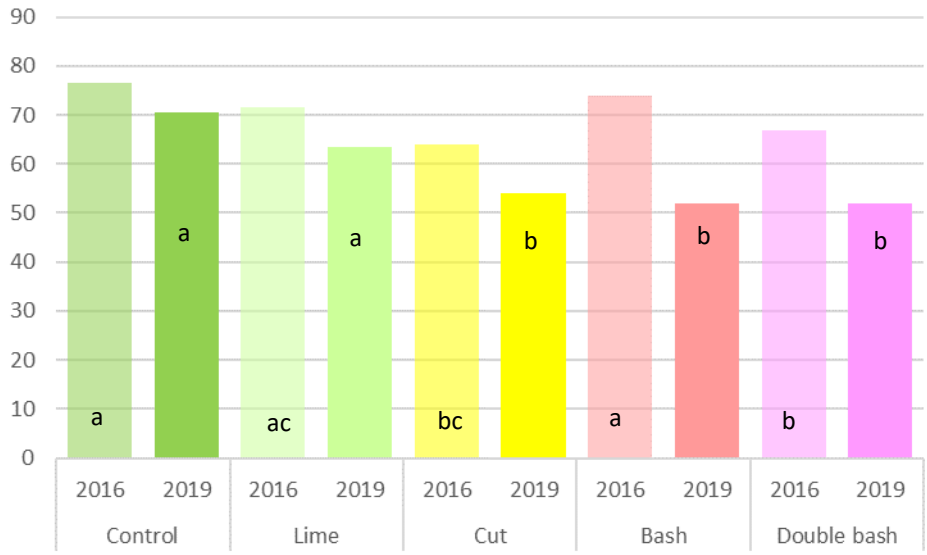


Figure 49. Mean (of plots) NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) score 2016 & 2019, by mechanical/liming treatment at Challacombe Farm, Devon. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

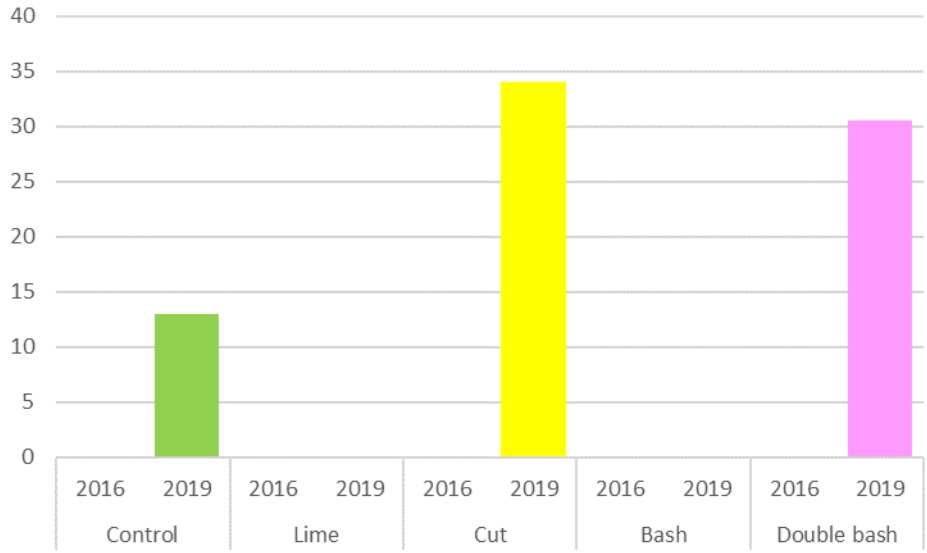


Figure 50. Mean (of plots) NVC U4 (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland) score 2016 & 2019, by mechanical/liming treatment at Challacombe Farm, Devon. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor

3.2.9 NVC SCORES AT CHALLACOMBE FARM, DEVON; CHEMICAL TREATMENT PLOTS

There were insufficient data collected in 2016 to derive baseline NVC communities for the plots at Challacombe Farm. The 2019 NVC community/ sub-community matches derived using Tablefit are given below (table 2) for each treatment. In 2019 all treatments scored highest as *very good* matches to U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community). The lowest scoring treatment was the Control, (score = 76), although this was only slightly short of the maximum scores of 83 (Asulam 1N and Metsulfuron 1N).

	NVC Community/sub community								
	U20	U20a	U20b	U20c	U 4	U 4a	U 4b	U 4c	U 4d
Control	67	**76**	55	61	58	41	41		
Asulam 1N	72	**83**	54	56	68	48	45	44	47
Amidosulfuron 0.5N	70	**82**	54	53	69	49	46	44	49
Amidosulfuron 1N	69	**80**	49	51	73	52	47	47	52
Metsulfuron 1N	74	**83**	54	54	66	45	46	41	42

Table 2. Tablefit percentage matches of 2019 data to NVC community/sub communities of chemical treatment small plots at Challacombe Farm. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor. The best matches are highlighted and in bold text

3.2.10 NVC SCORES AT FAWDON FARM, NORTHUMBERLAND; CHEMICAL TREATMENT PLOTS

There were insufficient data collected in 2016 to derive baseline NVC communities for the plots at Fawdon Farm. The 2019 NVC community/ sub-community matches derived using Tablefit are given below (table 3) for each treatment. The highest-scoring community matches for the plots are described here.

In 2019, the best match for all but the Control treatment was U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community), The plots treated with Amidosulfuron 1N and Metsulfuron 1N were rated as poor matches and the Asulam 1N and Amidosulfuron 0.5N treated plots were rated as fair matches. The Control treatment was a good match to U20c ((*Pteridium aquilinum – Galium saxatile*; species-poor sub-community).

	NVC Community/sub community				
Treatment	U20	U20a	U20b	U20c	U 4
Control	41	33	39	**56**	
Asulam 1N	44	**48**	37	36	27
Amidosulfuron 0.5N	37	**40**	32	32	
Amidosulfuron 1N	38	**39**	31	31	
Metsulfuron 1N	35	**36**	26	31	

Table 3. Tablefit percentage matches of 2019 data to NVC community/sub communities of chemical treatment small plots at Fawdon Farm. Matches of scores to communities are described as follows: 70-100 - Very Good, 50-69 – Good, 40-49 – Fair, 30-39 – Poor, 01-29 - Very Poor. The best matches are highlighted and in bold text

3.3 GPS AND UAV-MAPPED BRACKEN EXTENT WITHIN PLOTS AT INGRAM FARM, NORTHUMBERLAND

3.3.1 GPS-MAPPED

Figures 51-53 (below) show the GPS-mapped extent of bracken cover at 100% with vigour score 7 or above 2016-2019. A visual comparison of mapped bracken cover from 2016 to 2019 suggests that bracken cover in all plots has fallen year-on-year. Most noticeable from 2017 & 2018 are the reduction in bracken cover in each of the Double-bash plots (figures 51 & 52) and a subsequent increase in cover for those plots in 2019 when the treatment was not applied. Other noticeable features include footpaths and animal tracks, which are often associated with scrapes at the base of terraces.

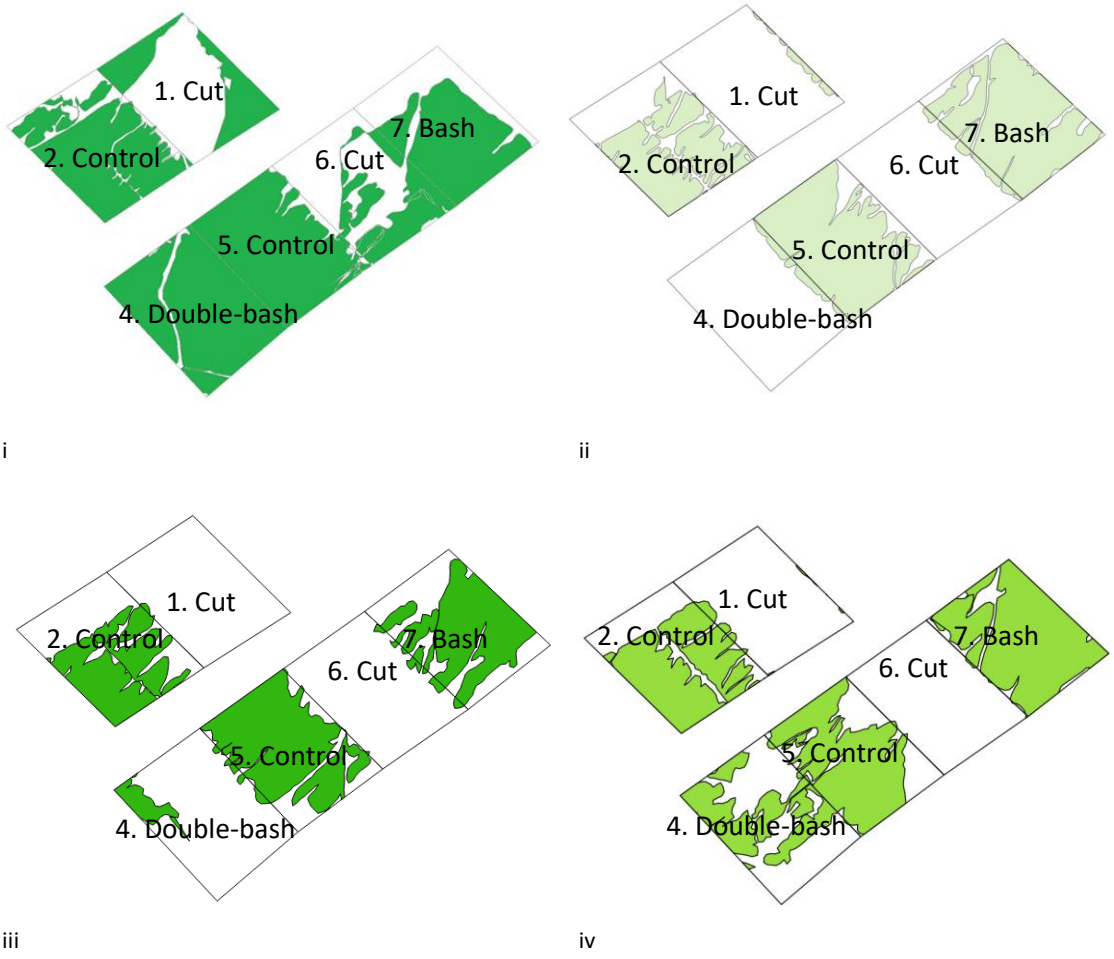


Figure 51. Ground-mapped extent of bracken cover at Ewe Hill (sheep grazing), Ingram Farm, Northumberland, plots 1-2, 4-7 (i) 2016, (ii) 2017, (iii) 2018 & (iv) 2019. Green-shaded portions indicate mapped extent of 100% bracken cover at vigour score 7 or above within plots

Figure 52. Ground-mapped extent of bracken cover at Ewe Hill (sheep grazing), Ingram Farm, Northumberland, plots 3 & 8 (i) 2016, (ii) 2017, (iii) 2018 & (iv) 2019. Green-shaded portions indicate mapped extent of 100% bracken cover at vigour score 7 or above within plots

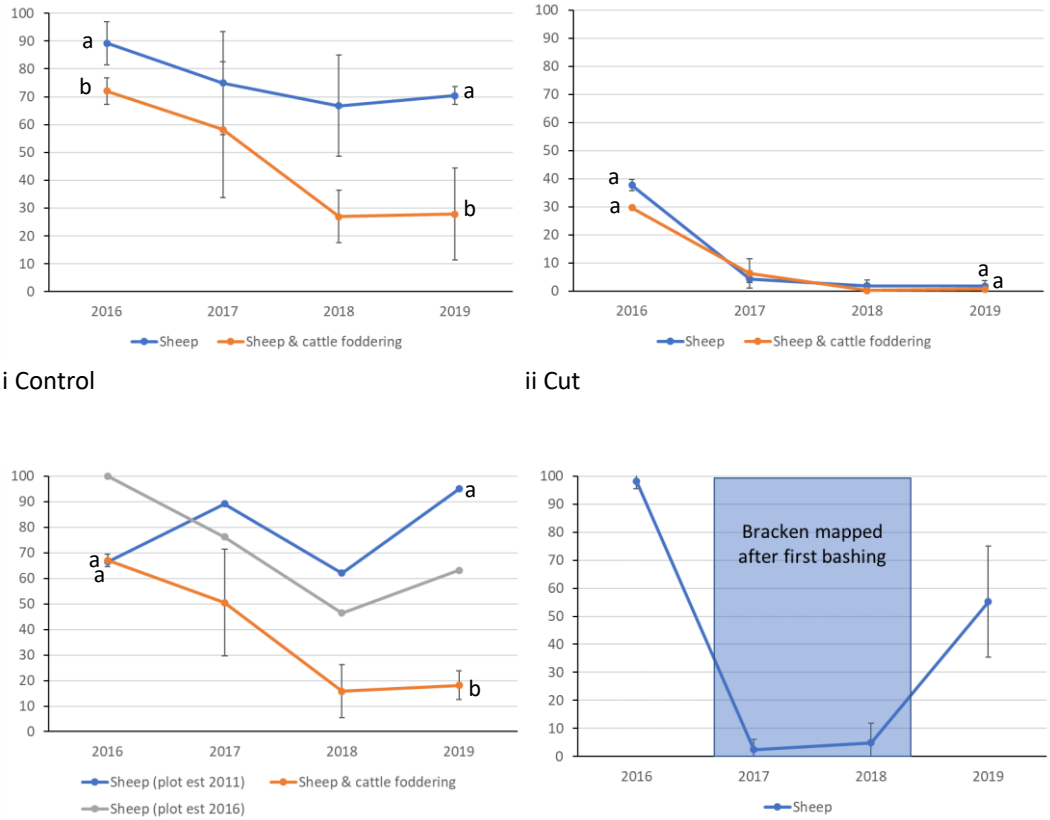
Figure 53. Ground-mapped extent of bracken cover at Wether Hill (sheep grazing and winter cattle foddering), Ingram Farm, Northumberland plots 9-14 (i) 2016, (ii) 2017, (iii) 2018 & (iv) 2019. Green-shaded portions indicate mapped extent of 100% bracken cover at vigour score 7 or above within plots

The year-to-year ground-mapped percentages of full cover bracken with a vigour score of 7 or above are shown in figure 54, below.

In 2016, five years after treatments started, there were a number of significant differences between treatments. In 2016 and 2019 there was significantly lower cover (2016: $P < 0.01$, 2019: $P < 0.001$) between the Control treatments on Wether Hill (winter cattle foddering) and those on Ewe Hill (no winter cattle foddering). In 2019, the cover in the Bash treatment Wether Hill was also significantly lower compared with Ewe Hill ($P < 0.001$).

Analyses of 2016 differences between treatments were undertaken separately for Wether Hill (winter cattle foddering) and Ewe Hill (no winter cattle foddering). Full bracken cover with vigour 7+ were significantly lower than the Control for each of the Cut plots and Bash plots (all $P < 0.001$). The same relationships were observed again in 2019, with the exception of Control vs. Bash on Wether Hill, where cover was not significantly different. This is likely to be due to the reduction in bracken cover on the plots overall as a result of the cattle foddering.

Bracken cover in 2016 was also significantly lower in the Cut treatment compared with the Bash treatment ($P < 0.001$). In 2016 there was significantly *higher* cover in the new, untreated Double-bash treatment plots compared with the Control ($P < 0.05$). This is likely to be a function of the 100% bracken cover in Double Bash plot 8, further west up Ewe Hill, away from the bare terraces used as animal scrapes in the Control plots and other treatments (see figures 51i & 52i, above). The quadrat-based survey did not show a comparable difference in bracken cover, because placement of quadrats deliberately avoided paths and scrapes (see figure 13, section 3.1.2, above).



i Control

ii Cut

iii Bash

iv Double-bash

Figure 54. 2016-2019 ground-mapped extent of 100% bracken cover at vigour score 7 or above within, split according to treatment (i) Control, (ii) Cut, (iii) Bash & (iv) Double-bash, Ingram Farm, Northumberland

3.3.2 UAV-MAPPED

Figures 55-61 (below) show the UAV-mapped normalized difference vegetation index (NDVI) mean scores per plot at Ingram Farm in July 2019. The yellow and green areas have higher NDVI scores (0.80-0.94). On Wether Hill, the areas in yellow appear broadly to correspond with areas known to have high bracken cover. On Ewe Hill it is the areas in green and yellow which appear to correspond with areas known to have high bracken cover. The relationships between the different ways of recording bracken are considered in section 3.3.3, below.

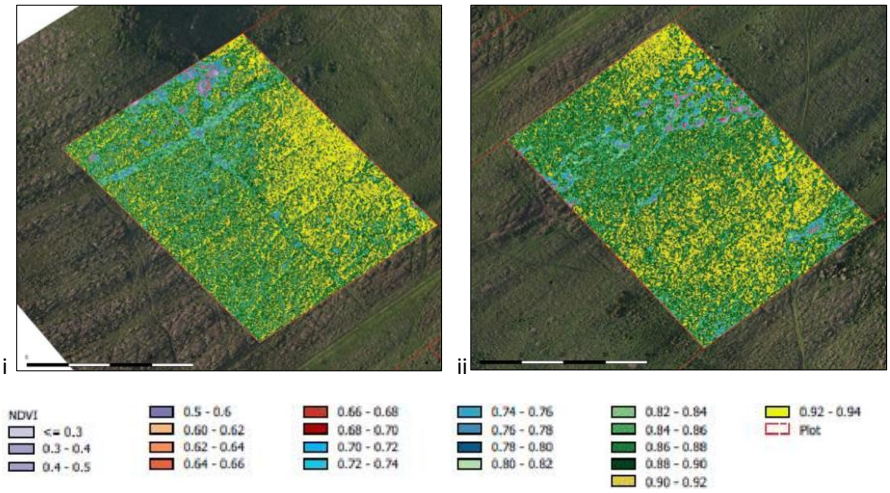


Figure 55. 2019 NDVI raster maps and colour key for Control plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 2, (ii) plot 5

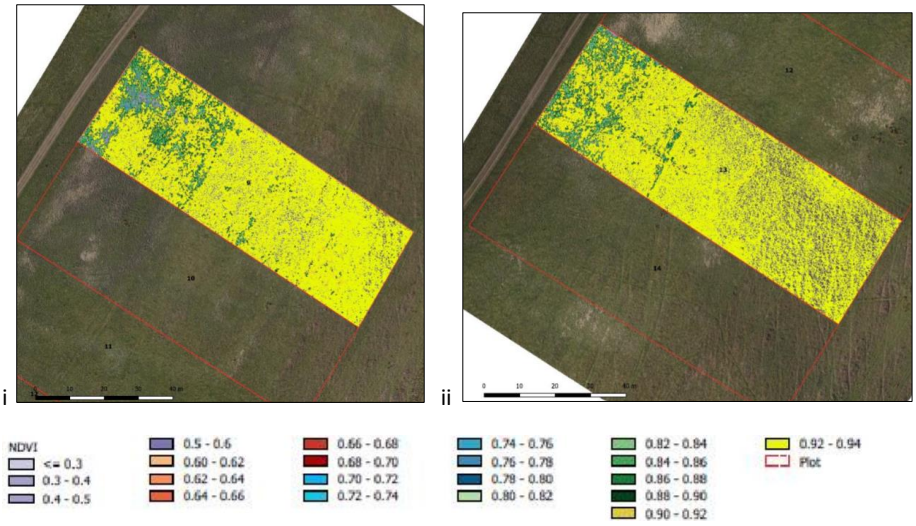


Figure 56. 2019 NDVI raster maps and colour key for Control plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 9, (ii) plot 13

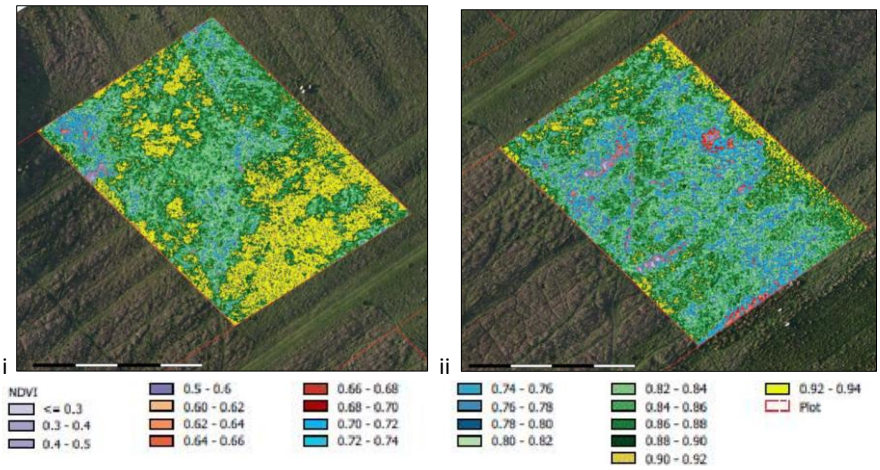


Figure 57. 2019 NDVI raster maps and colour key for Cut plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 1, (ii) plot 6

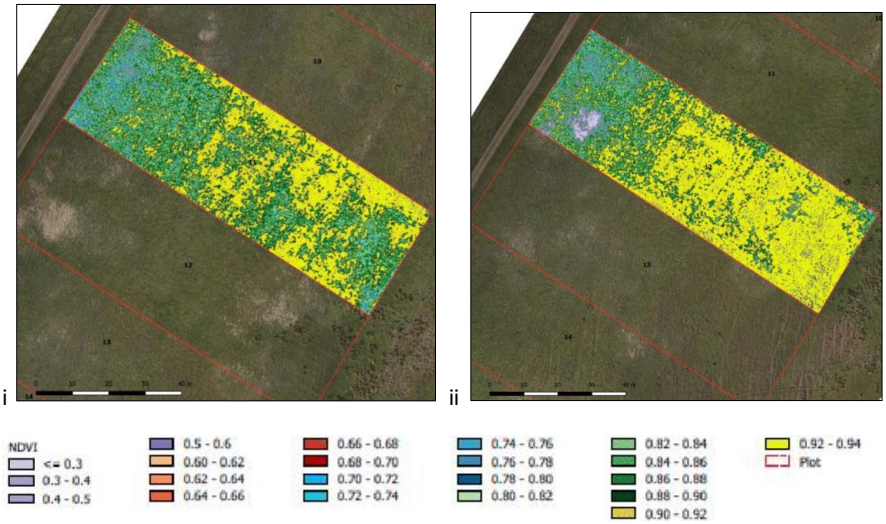


Figure 58. 2019 NDVI raster maps and colour key for Cut plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 11, (ii) plot 12

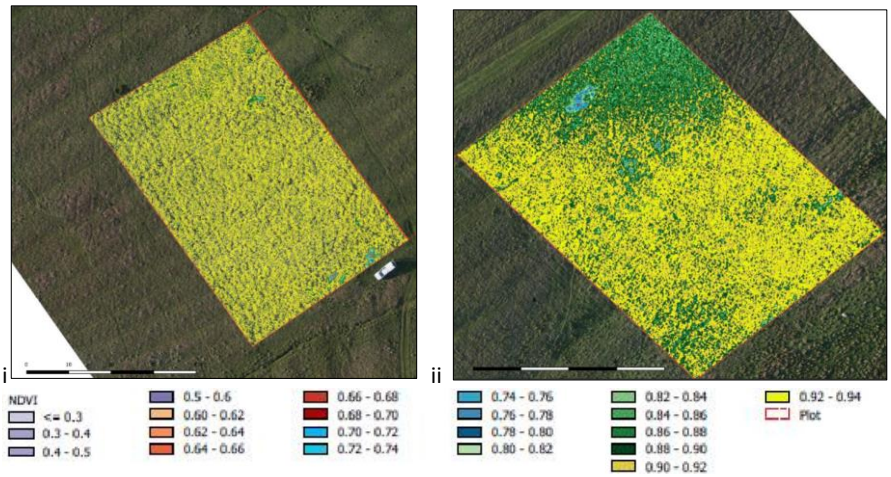


Figure 59. 2019 NDVI raster maps and colour key for Bash plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 3, (ii) plot 7

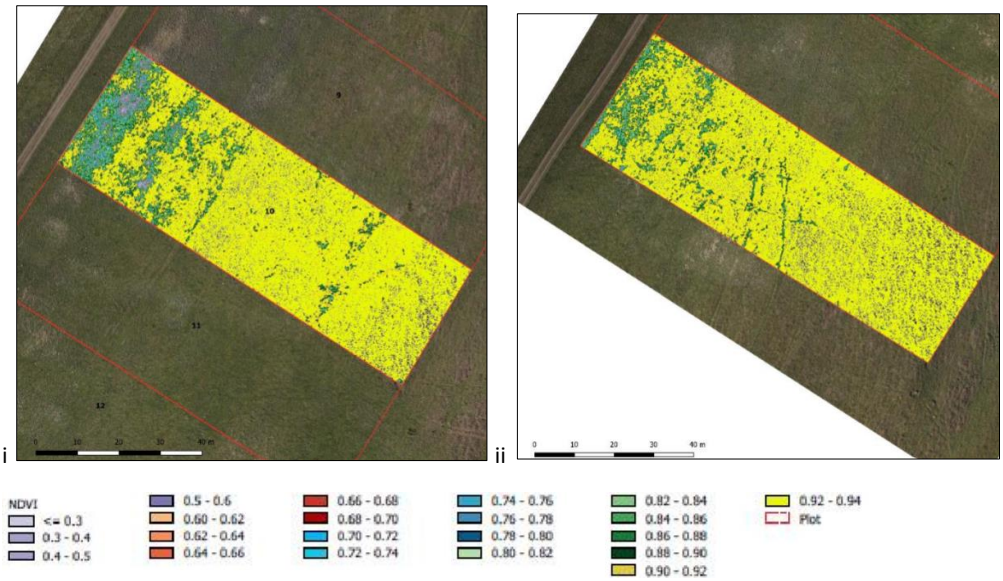


Figure 60. 2019 NDVI raster maps and colour key for Bash plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 10, (ii) plot 14

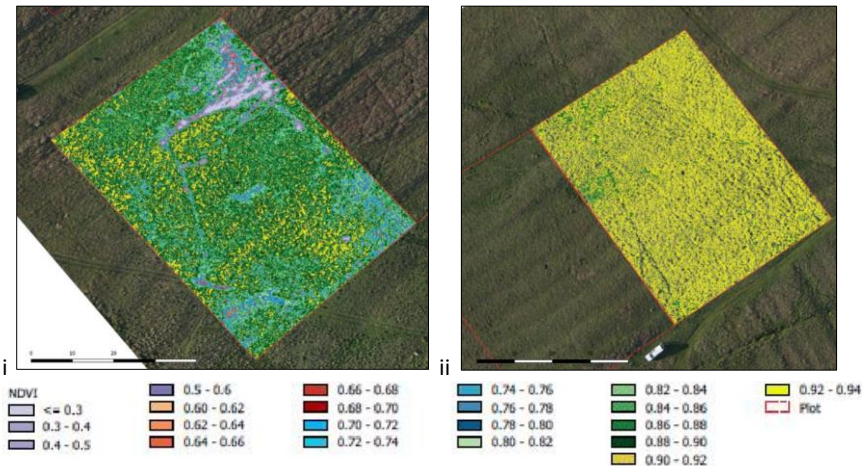


Figure 61. 2019 NDVI raster maps and colour key for Double-bash plots on Ewe Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 4, (ii) plot 8

3.3.3 COMPARISON OF BRACKEN COVER MAPPED BY GPS VS UAV AT INGRAM FARM, NORTHUMBERLAND

Initially, GPS-mapped bracken data (stands with 100% cover & vigour 7+) was compared with the bracken cover data obtained from quadrats to test for an expected positive correlation. The regression model showed a strong positive correlation (R^2 = 0.83, figure 62, below).

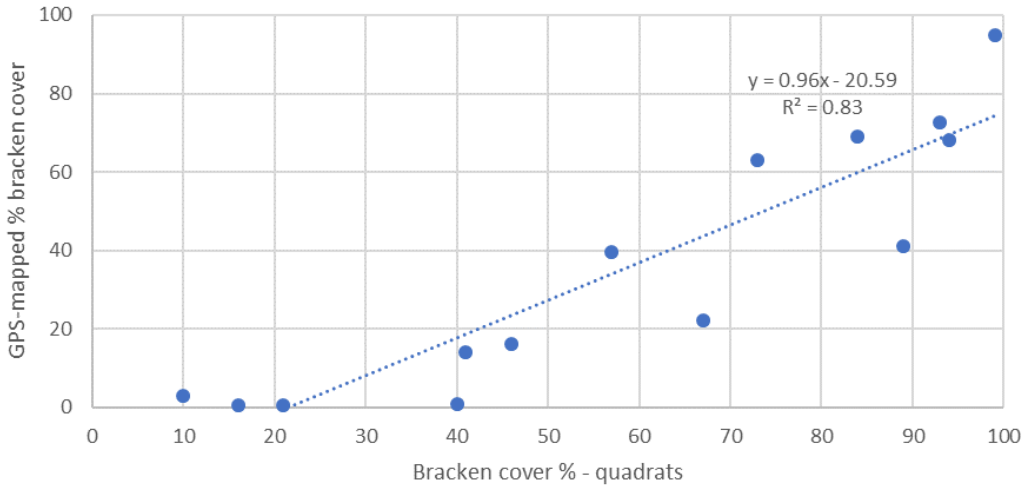


Figure 62. Linear regression of 2019 ground-mapped extent of 100% bracken cover at vigour score 7 or above vs. 2019 mean bracken cover per plot (measured by quadrats), Ingram Farm, Northumberland

Percentage bracken cover from quadrat data was then compared with mean NDVI scores per plot to test for a positive correlation. The linear regression model showed a positive correlation, but this was weak (R^2 = 0.06). Further investigation showed that the NDVI means on Wether Hill were higher on average than those on Ewe Hill (see visual examples in the Control plots, figures 52 & 53 above). Regression models were then fitted for each site (hill), with the resulting models showing a far stronger positive correlation between bracken cover measured by quadrats and NDVI mean scores (R^2 = 0.45, Ewe Hill and R^2 = 0.841, Wether Hill, figure 63, below). When the data for plots 3 and 8 (see oval in figure 63, below) further up Ewe Hill were removed from the model, the R^2 value for the Ewe Hill plots increased from 0.45 to 0.65.

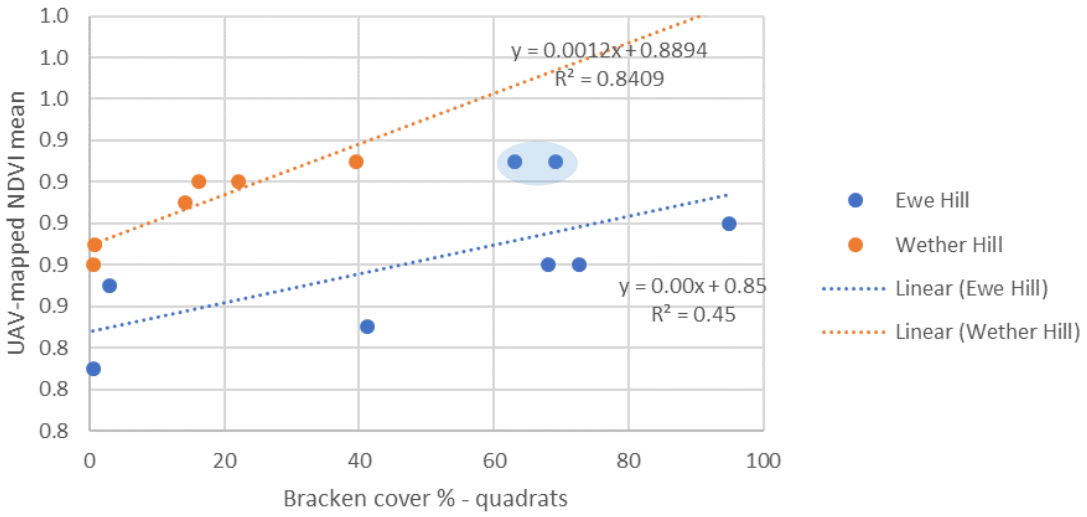


Figure 63. Linear regression of 2019 NDVI mean score per plot vs. 2019 mean bracken cover per plot (measured by quadrats), split according to treatment location at Ingram Farm, Northumberland. Blue oval denotes the data for plots 3 & 8 on Ewe Hill, which are further up the hill from the other six plots on Ewe Hill

GPS-mapped bracken (stands with 100% cover & vigour 7+) were then tested for an expected positive correlation with UAV-recorded vegetation cover, again, considering Ewe Hill and were compared to see if there was also an expected positive correlation.

Initial inspection of the NDVI raster maps and data suggested that the NDVI mean was higher in the plots on Wether Hill compared with Ewe Hill. Each plot's mean NDVI was plotted against mapped extent of bracken for each plot, and a linear regression model fitted. Although there was a positive correlation the relationship was weak, with an R^2 of 0.0889. The plot mean NDVI data for each site at Ingram Farm were then considered separately. Linear regression for each site produced a far better fit, with higher R^2 values for each of the fitted lines (see figure 64, below).

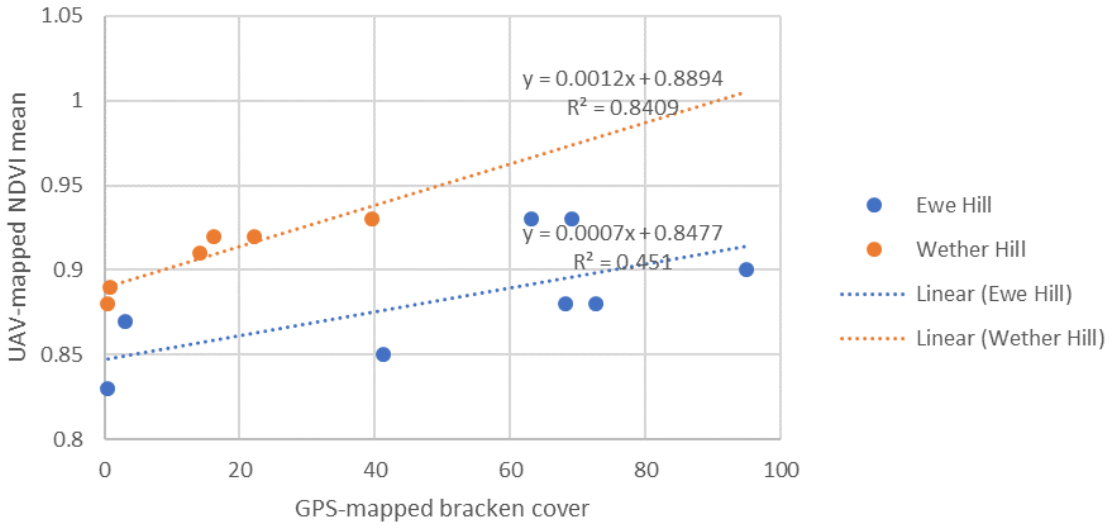


Figure 64. Linear regression of 2019 ground-mapped extent of 100% bracken cover at vigour score 7 or above vs. 2019 NDVI mean score per plot, split according to treatment location at Ingram Farm, Northumberland

3.4 ANALYSIS OF DISPLACEMENT AND DAMAGE TO THE PROXY ARCHAEOLOGICAL REMAINS AND GROUND

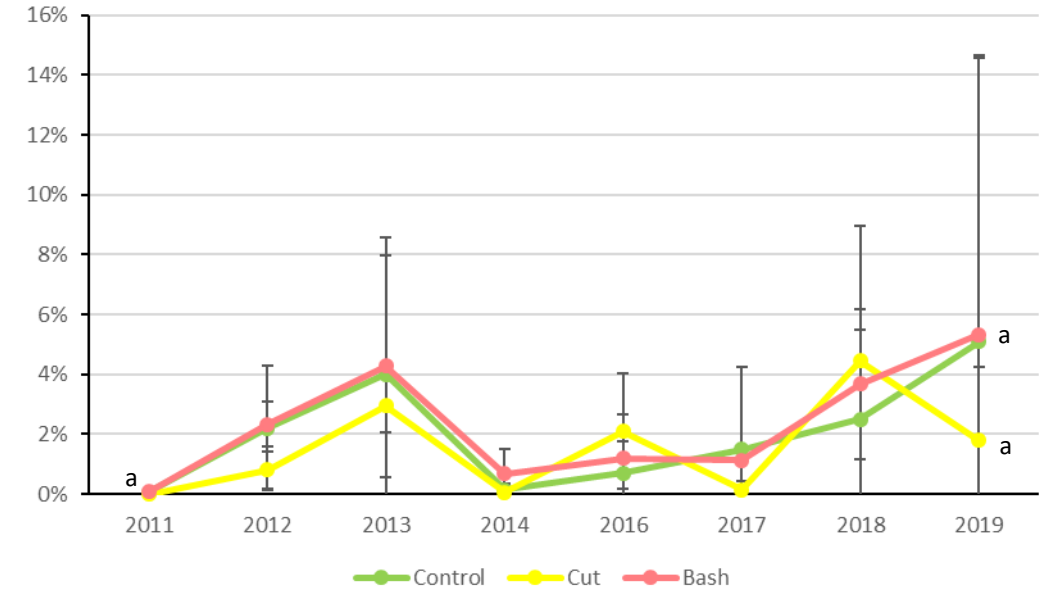
This section presents analysis of damage and displacement of the ground in the plots at Ingram Farm, Northumberland, based on measurements taken in quadrats and UAV surveys.

The section also provides assessments of displacement and damage to the proxy archaeological remains (concrete cylinders) that were part-buried in plots at all sites in 2016. These analyses are based on movement scores derived from changes in tilt angle, azimuth, plus larger-scale displacement of the concrete cylinders at Ingram Farm, Fawdon Farm and Challacombe Farm. The end of this section provides analysis of visual assessments of physical damage to the cylinders.

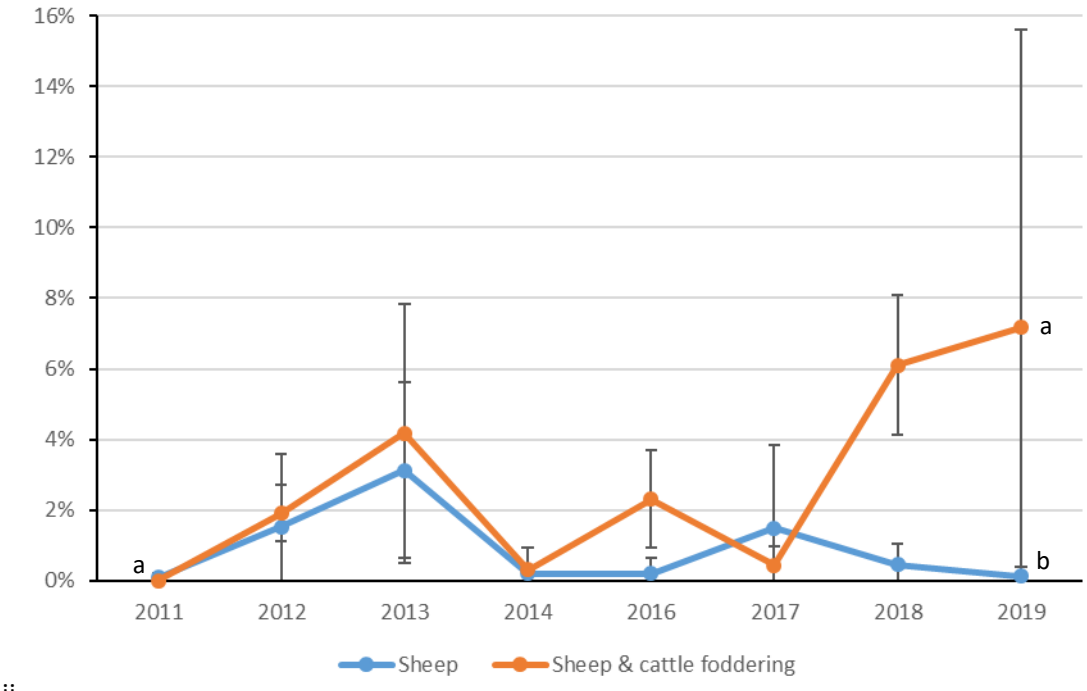
3.4.1 *QUADRAT-BASED ASSESSMENTS OF GROUND DISTURBANCE*

Analysis of pre-existing experimental plots at Ingram Farm, Northumberland

In 2011 there was only one quadrat in one plot with any bare ground, and no disturbed ground. In 2019, bare ground cover and disturbed ground cover was significantly higher on the Wether Hill plots where winter cattle foddering takes place (figures 65ii & 66ii, below). In 2019 there were no significant differences between mechanical treatments.

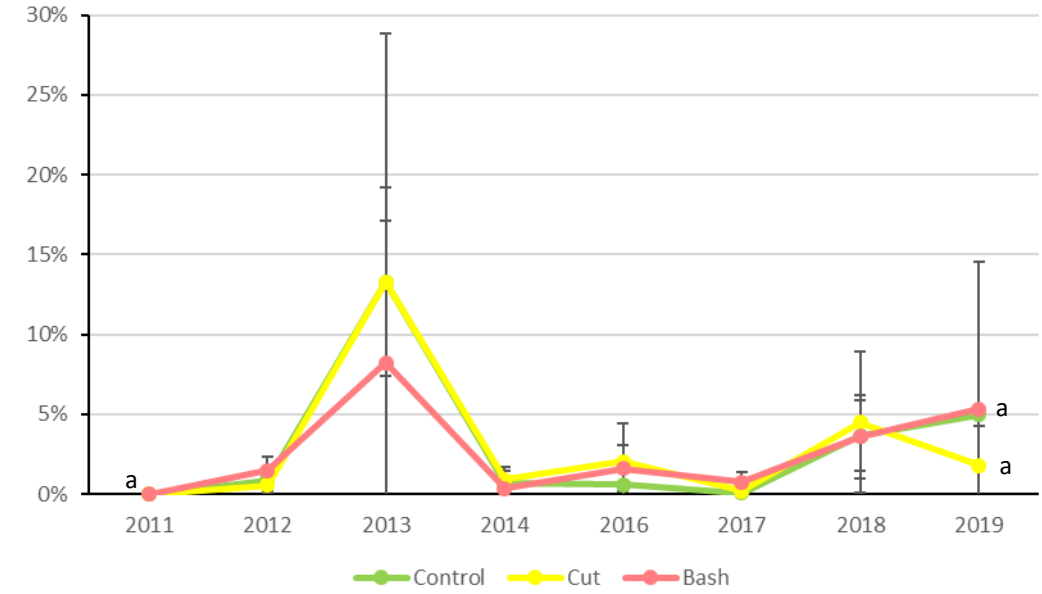


i

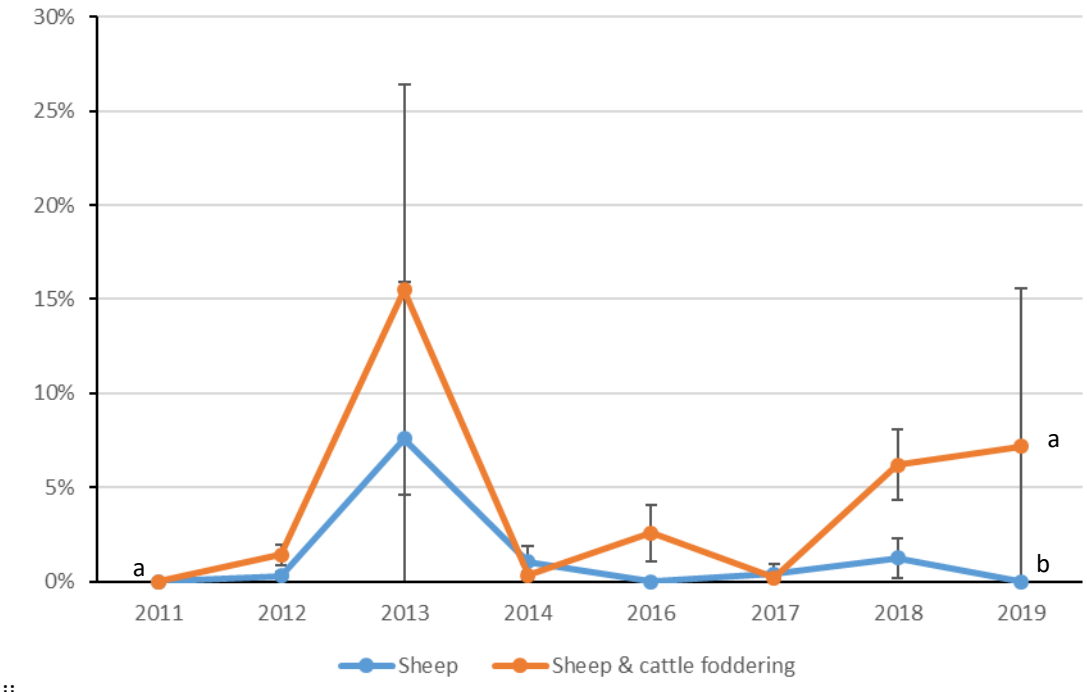


ii

Figure 65. Mean bare ground cover (%) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016



i



ii

Figure 66. Mean (± standard deviation) disturbed ground cover (%) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) and grazing treatment (ii). Excludes the Double-Bash treatment plots and Bash plot established in 2016

Analysis of environmental data at the new experimental plots, Ingram Farm, Northumberland

Several measures of damage to the historic environment were recorded within each quadrat; % cover of stones % of bare ground and % disturbed ground. In 2016 and 2019 no stones or disturbed ground were recorded in the quadrats in these treatment plots. There was no bare ground recorded in 2016 and in 2019, bare ground was only recorded in one quadrat.

3.4.2 *DISPLACEMENT OF CONCRETE CYLINDERS*

Figures 67-72, below show the frequencies, by treatment, of concrete cylinder displacement scores. Displacement scores range from 1-14, with 1 indicating least displacement, and 14 most displacement. A description of how displacement scores were calculated is given above in section 2.1.6, and summarised in table 4, below:

Score 1-8 if cylinder still in hole, highest score from:	1 up to 8 for every additional 10-degree interval of tilt from original position
	1 if up to 41 degrees change in azimuth from original position, then increments of 1 up to 8 for every additional 20-degree interval from original position
9-14 if cylinder out of hole	score 9 if <50cm from original location, with increments of 1 for each 50cm, up to 14 for 250cm or more

Table 4. Summary of methodology for scoring cylinder displacement

Grazing treatment

The displacement of cylinders at Ingram Farm, Northumberland, was significantly higher on the Wether Hill where winter cattle foddering took place compared with Ewe Hill (figure 67, below, $P < 0.001$).

Physical/Liming treatments

There was significantly greater displacement of cylinders on the Cut treatment compared with the Control on Ewe Hill, Ingram Farm (no winter foddering, figure 68 below, $P < 0.001$) and Wether Hill, Ingram Farm (winter cattle foddering, figure 69 below, $P < 0.05$). Displacement was also significantly greater in the Cut treatment compared with the Control at Challacombe Farm, Devon (figure 70, below, $P < 0.05$).

Challacombe Farm saw a number of additional significant differences between treatments. There was significantly greater displacement in Cut treatment compared with the Bash treatment ($P < 0.05$). The Double-bash treatment also saw significantly greater displacement than the Bash and Control treatments ($P < 0.001$). The Liming treatment saw significantly greater displacement than the Bash and Control treatments ($P < 0.05$).

Chemical treatments

The concrete cylinder displacement scores for chemical treatment plots are shown below in figure 71 (Challacombe Farm, Devon) and figure 72 (Fawdon Farm, Northumberland). There were no significant differences in displacement score frequency distributions for the concrete cylinders sited in the chemical treatment plots at Challacombe and Fawdon Farms.

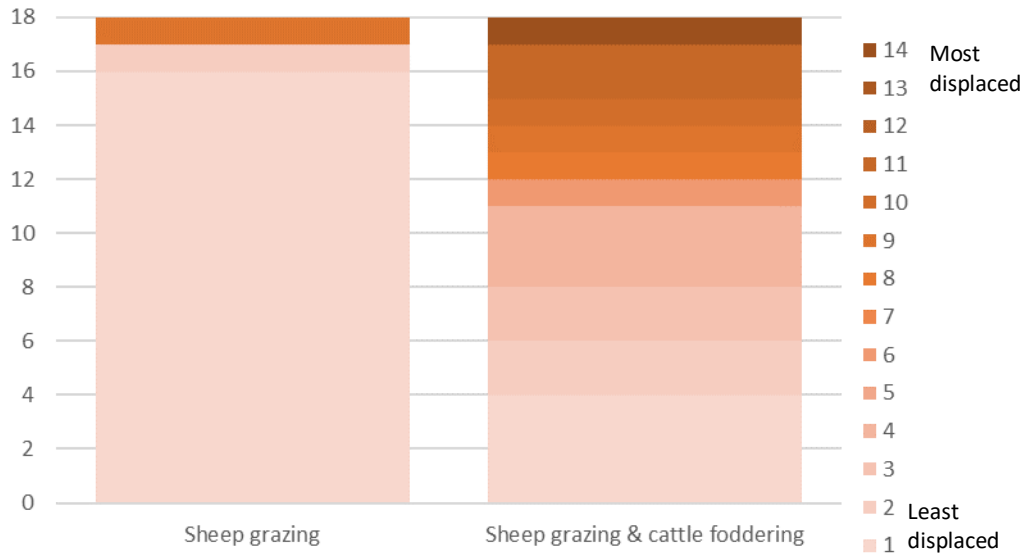


Figure 67. 2019 frequency distribution of cylinder displacement scores (1-14) Ewe Hill (grazing, no cattle foddering) vs. Wether Hill grazing & winter cattle foddering) at Ingram Farm, Northumberland

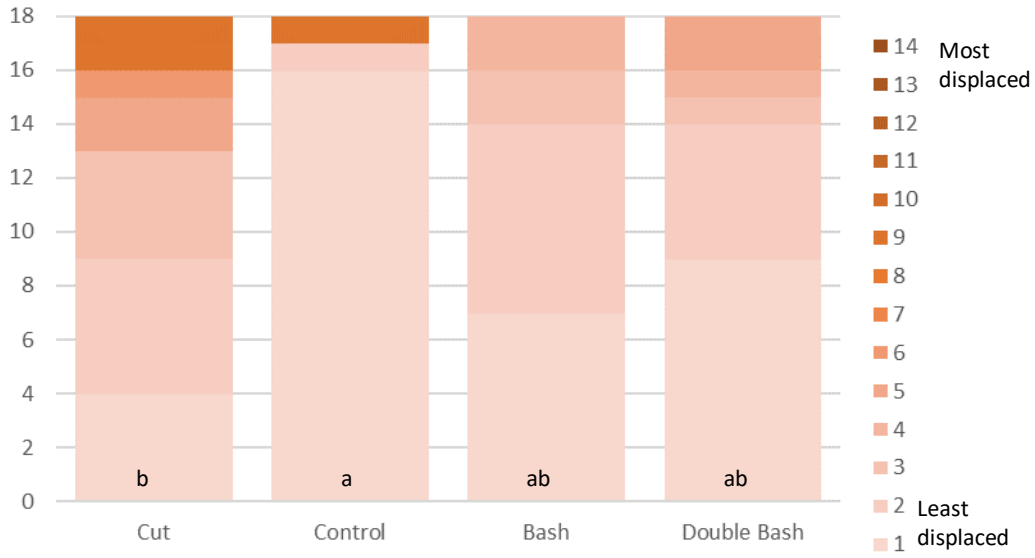


Figure 68. 2019 frequency distribution of cylinder displacement scores (1-14) Ewe Hill (grazing, no cattle foddering) at Ingram Farm, Northumberland

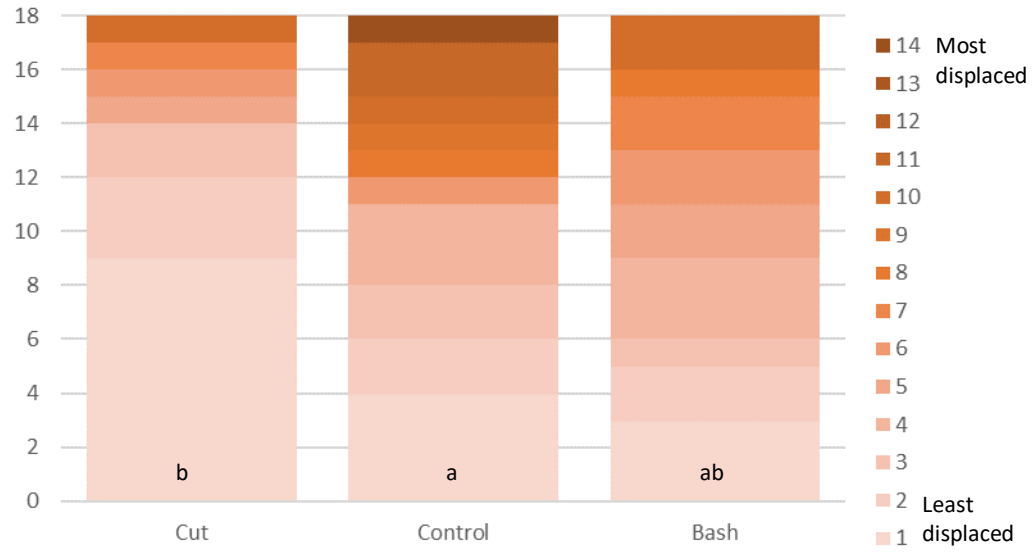


Figure 69. 2019 frequency distribution of cylinder displacement scores (1-14) Wether Hill (grazing & winter cattle foddering) at Ingram Farm, Northumberland

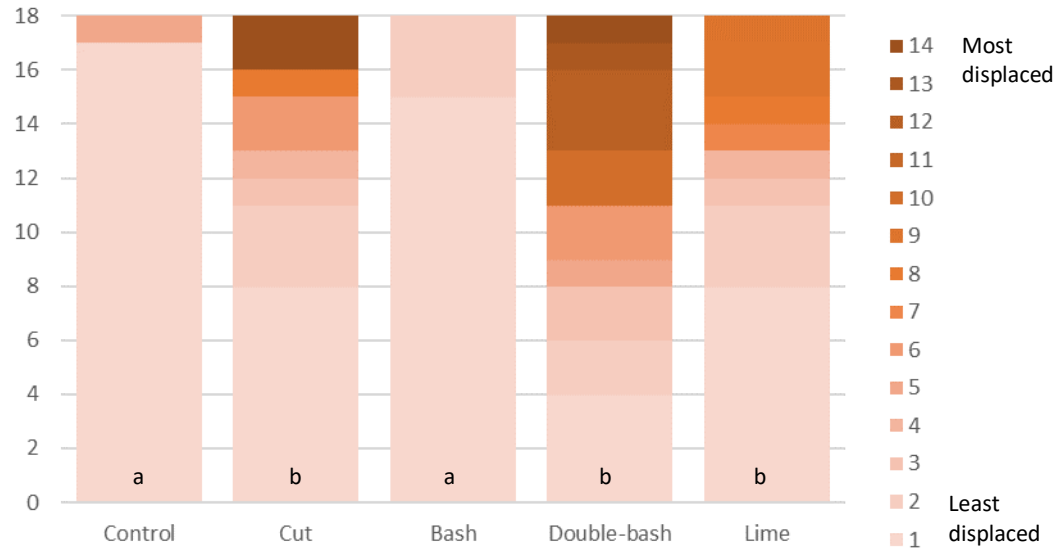


Figure 70. 2019 frequency distribution of cylinder displacement scores (1-14) for physical/liming treatments, Challacombe Farm, Devon

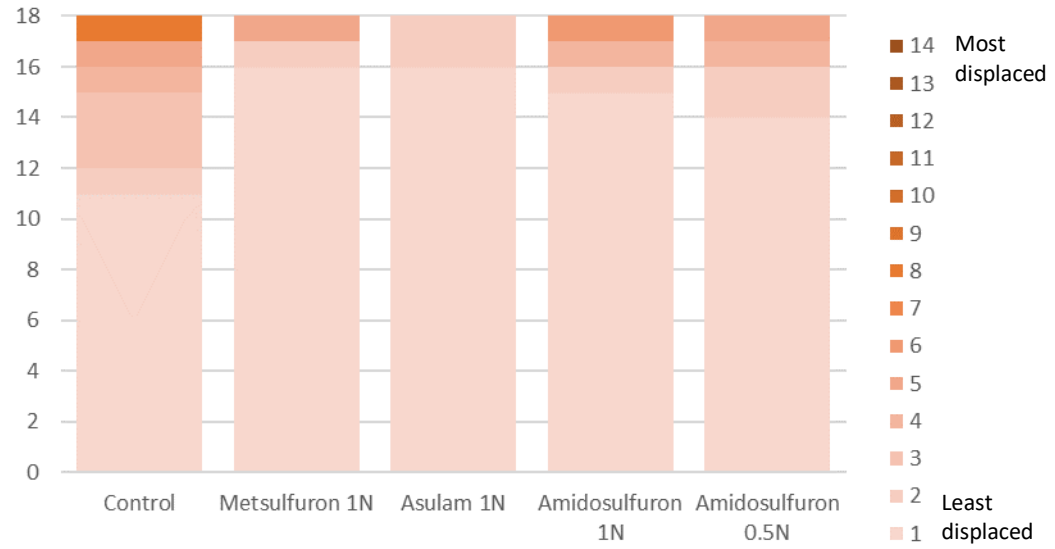


Figure 71. 2019 frequency distribution of cylinder displacement scores (1-14) for chemical treatments, Challacombe Farm, Devon

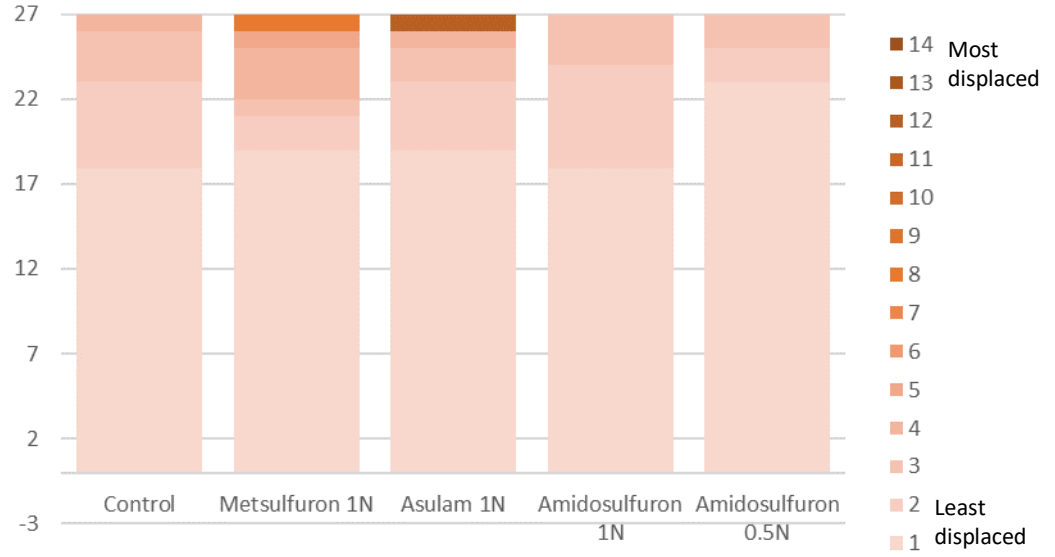


Figure 72. 2019 frequency distribution of cylinder displacement scores (1-14) for chemical treatments, Fawdon Farm, Northumberland

3.4.3 *VISUAL ASSESSMENT OF DAMAGE TO CONCRETE CYLINDERS*

Physical damage to cylinders was not found in any of the plots at Fawdon Farm and Challacombe Farm where chemical treatments had been applied (or the Control plots on those sites). Damage *was* found on cylinders in in many of the plots at Ingram Farm and the mechanical/liming treatment plots at Challacombe Farm. The exceptions at Ingram Farm were three of the Control plots (two on Ewe Hill and one on Wether Hill). The exceptions at Challacombe Farm (mechanical/liming treatments), were one Cut treatment plot, one Liming treatment plot and both Controls.

In general, at Ingram and Challacombe Farms, cylinder damage was limited to the upper part and top surface, although a small number of cylinders which had been 'uprooted' also had damage to the sides. Typical examples of cylinder damage are shown in figure 73, below, although a number of cylinders were damaged to a greater or lesser extent.

Figure 73. Examples of physical damage to cylinders at Challacombe Farm, following (i) bashing & (ii) cutting in 2016

Figures 74 & 75, below show, by treatment, the mean number of concrete cylinders per plot at Ingram and Challacombe Farms which showed visible damage following the treatments in 2016 and 2019. None of the cylinders showed signs of physical damage at Fawdon Farm or the Challacombe Farm chemical treatments. Pearson's Chi-squared test with Yates' continuity correction showed no significant difference between the number of cylinders damaged on the Ingram Farm, Wether Hill plots where cattle foddering took place compared with those on the Ingram Farm Ewe Hill plots where cattle foddering did not take place. There were insufficient data to test for differences between Cut, Bash, Double-bash, Liming and Control treatments at Ingram and Challacombe farms so these data were aggregated and the Liming treatment excluded. Pearson's Chi-squared test with pairwise post-hoc testing showed that there was a significantly greater proportion of damaged cylinders at each site between all treatments except Bash vs. Double-bash (all $P < 0.001$, except Cut vs Bash and Cut vs. Control which were $P < 0.01$).

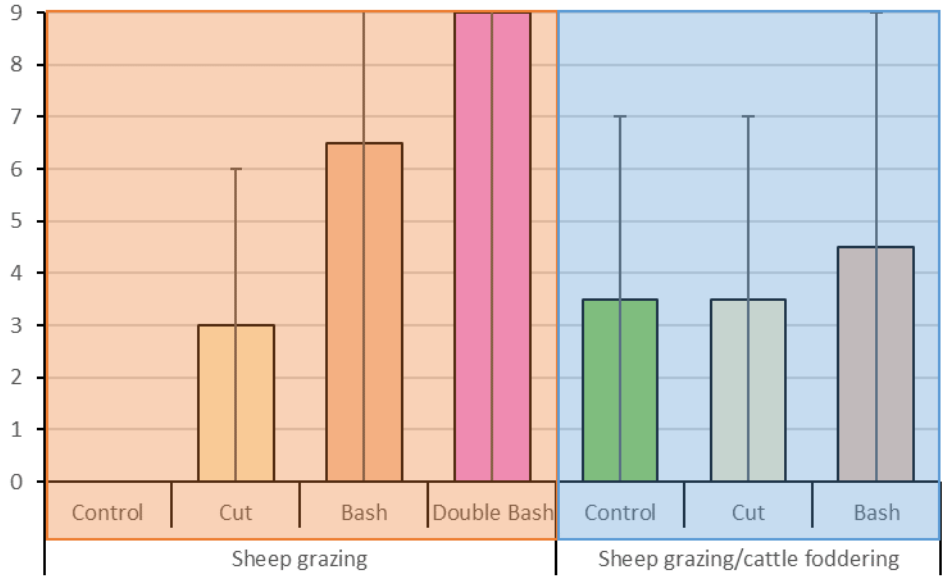
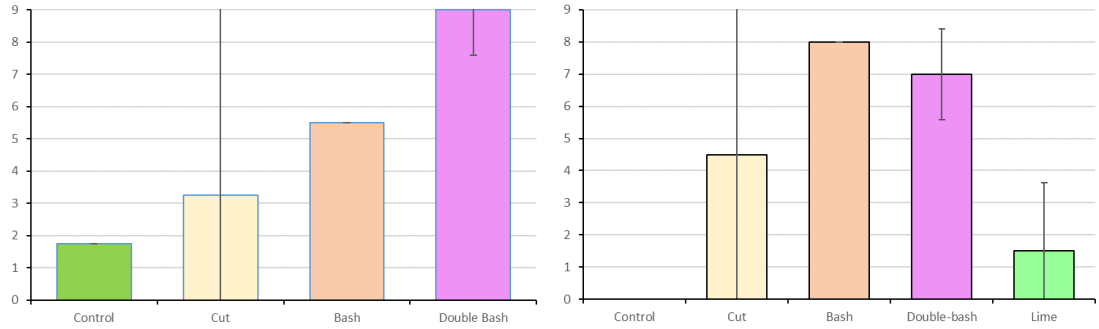


Figure 74. Comparison between plots, of mean (± standard deviation) number of physically damaged cylinders 2016-2019 at Ingram Farm, mechanical treatments, split by grazing/foddering treatments



i ii

Figure 75. Comparison between plots, of mean (+- standard deviation) number of physically damaged cylinders 2016-2019 at (i) Ingram Farm & (ii) Challacombe Farm mechanical/liming treatments

3.4.4 *UAV-BASED ASSESSMENTS OF DAMAGE TO THE GROUND*

This section presents maps and analysis of 2016-2019 UAV-measured terrain height differences recorded and analysed by TerraDrone for Historic England. Figures 76-87 below show the plots at Ingram Farm and Challacombe Farm, and table 5, below shows the plot-by-plot recorded mean height changes 2016-2019. The mean height change data from these figures forms the basis of the analysis in section 3.4.5, below, which compares some of the different measures of damage to the historic environment with the mean changes in ground height from 2016-2019.

The figures below clearly show cultivation terraces, walls, trees & shrubs, paths and other ground features. These are prominent, relatively static features in the landscape which have been recorded as changing in height between 2016 and 2019, to a different extent than the ground in the interstices between features.

The areas of ground with a small (±6cm) measured change in ground height tended to correspond with areas of low bracken cover and high grass cover. Areas with high bracken cover showed moderate (±10cm-20cm) increases or decreases in measured height change depending on site or block of plots recorded in a given flight. At Challacombe Farm, the greatest recorded increases in ground height (25cm-100cm) were often trees/shrubs and the field boundary walls on the edges of the plots.

Plot	Treatment	Mean height change (m)
1	Cut	-0.091
2	Control	-0.126
3	Double-bash	0.251
4	Double-bash	-0.119
5	Control	-0.05
6	Cut	-0.051
7	Bash	-0.09
8	Bash	0.165
9	Control	0.127
10	Bash	0.134
11	Cut	0.109
12	Cut	0.087
13	Bash	0.097
14	Control	0.115

i

Plot	Treatment	Mean height change (m)
2	Cut	-0.075
3	Double-bash	-0.134
4	Bash	-0.18
5	Control	-0.153
6	Lime	-0.096
7	Double-bash	-0.058
8	Control	-0.214
9	Lime	-0.103
10	Cut	0.026
11	Bash	-0.084

ii

Table 5. Mean changes in UAV-measured ground height per plot (m) at (i) Ingram Farm, Northumberland & (ii) Challacombe Farm, Devon

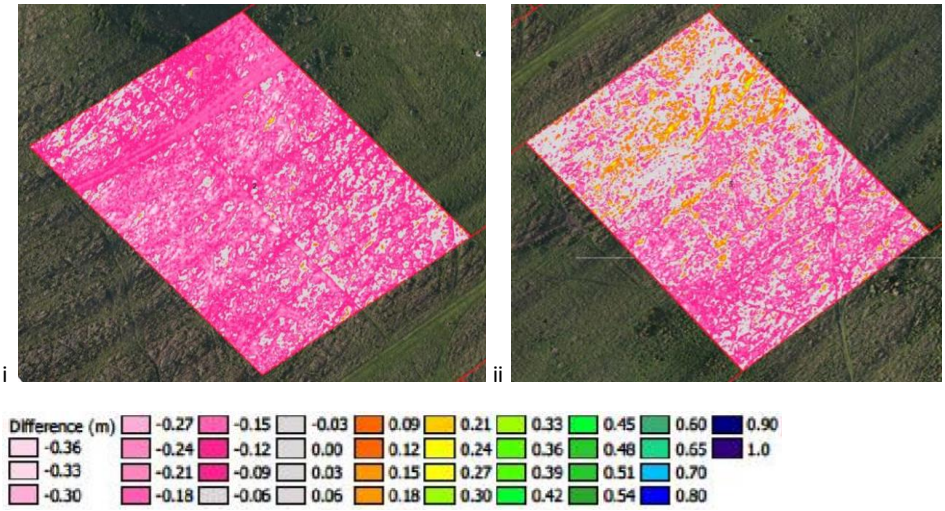


Figure 76. 2016-2019 height change (m) maps for Control plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 2, (ii) plot 5

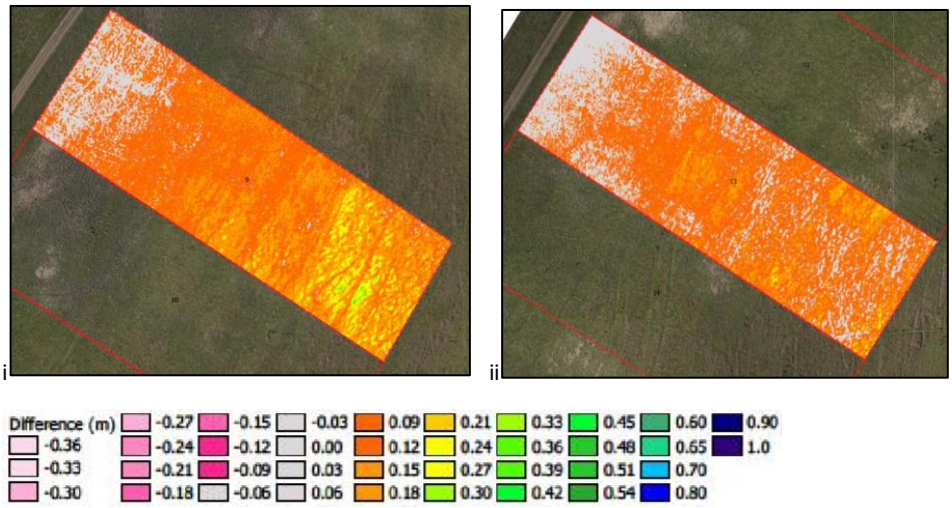


Figure 77. 2016-2019 height change (m) maps for Control plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 9, (ii) plot 13

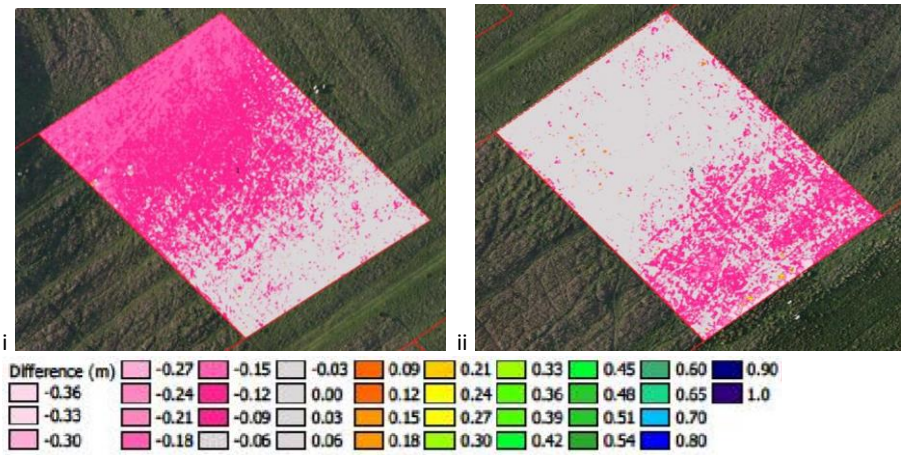


Figure 78. 2016-2019 height change (m) maps for Cut plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 1, (ii) plot 6

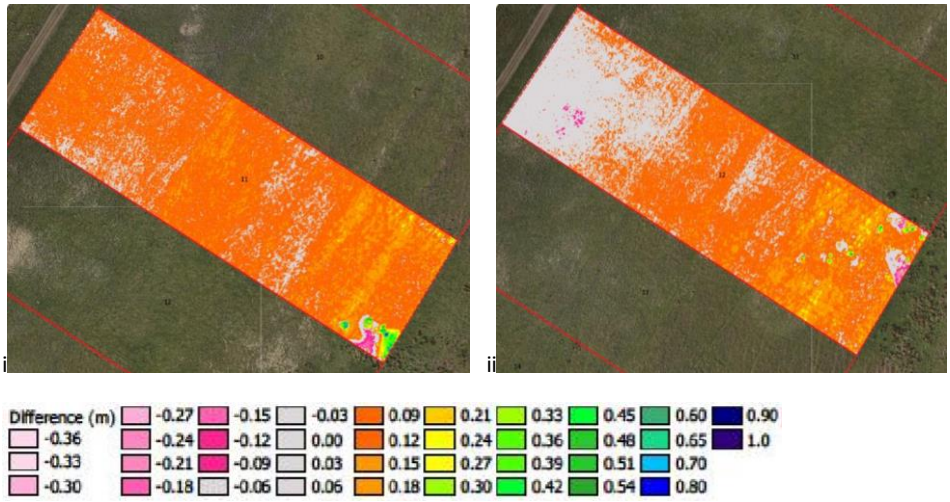


Figure 79. 2016-2019 height change (m) maps for Cut plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 11, (ii) plot 12

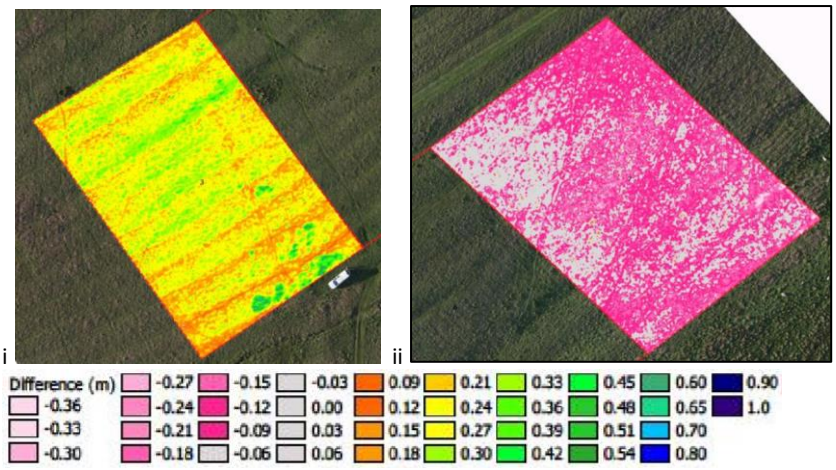


Figure 80. 2016-2019 height change (m) maps for Bash plots on Ewe Hill (sheep grazing), Ingram Farm, Northumberland (i) plot 3, (ii) plot 7

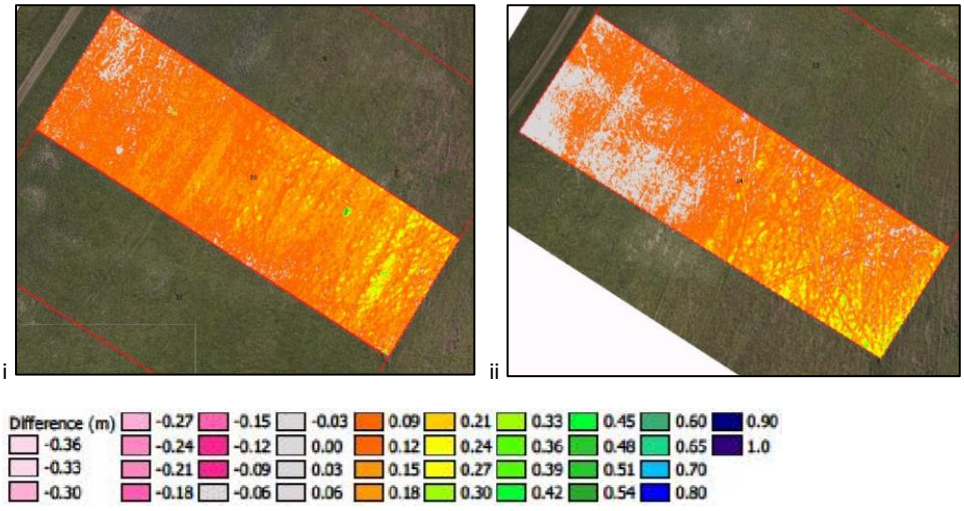


Figure 81. 2016-2019 height change (m) maps for Bash plots on Wether Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 10, (ii) plot 14

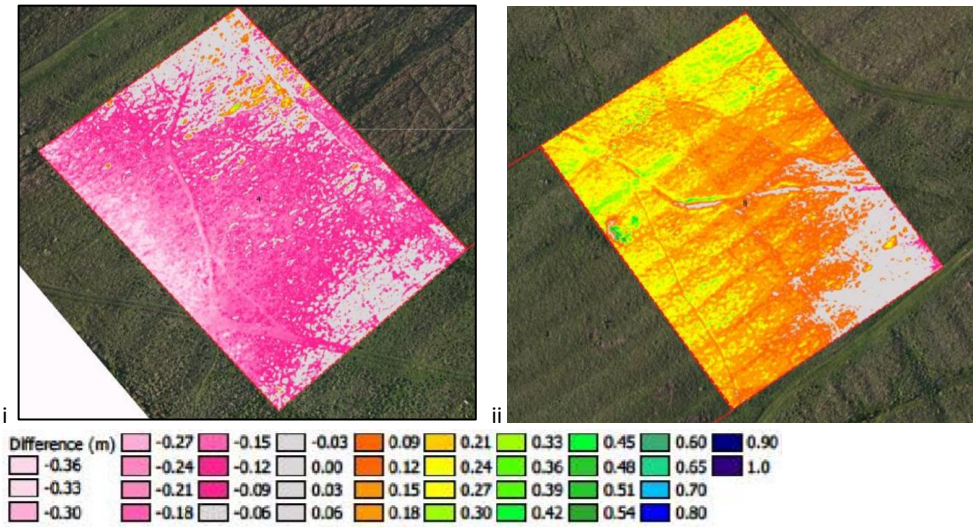


Figure 82. 2016-2019 height change (m) maps for Double-bash plots on Ewe Hill (sheep grazing & cattle foddering), Ingram Farm, Northumberland (i) plot 4, (ii) plot 8

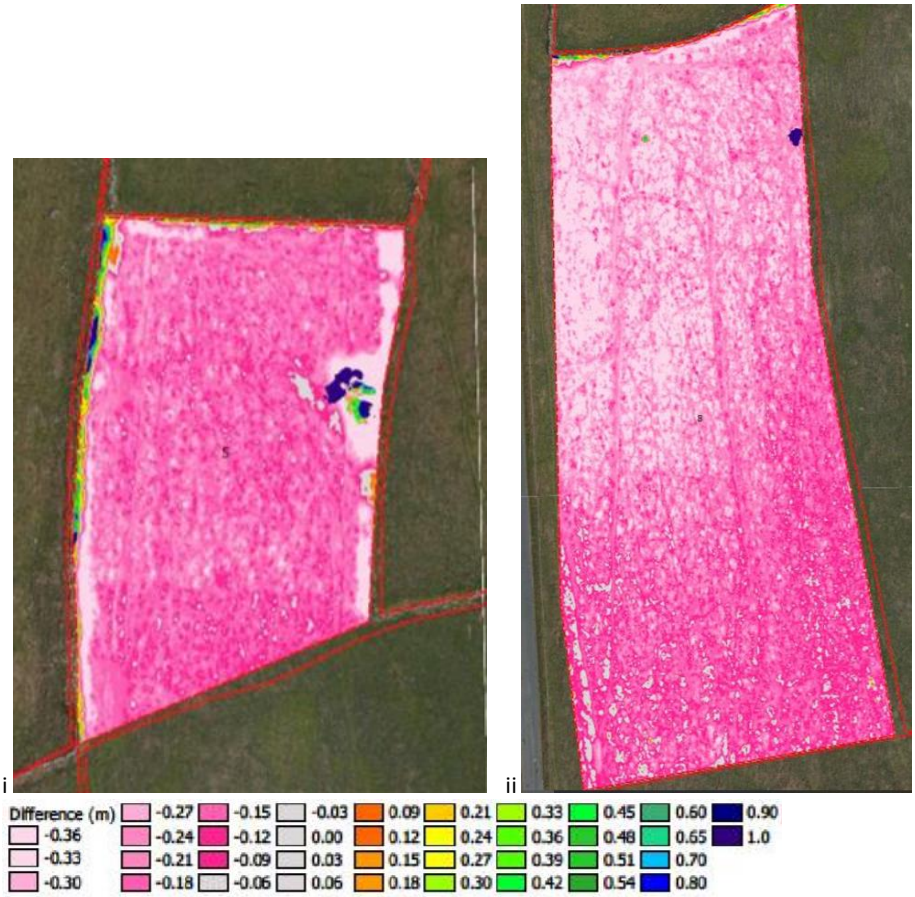


Figure 83. 2016-2019 height change (m) maps for Control plots, Challacombe Farm, Devon (i) plot 5, (ii) plot 8. Not to scale

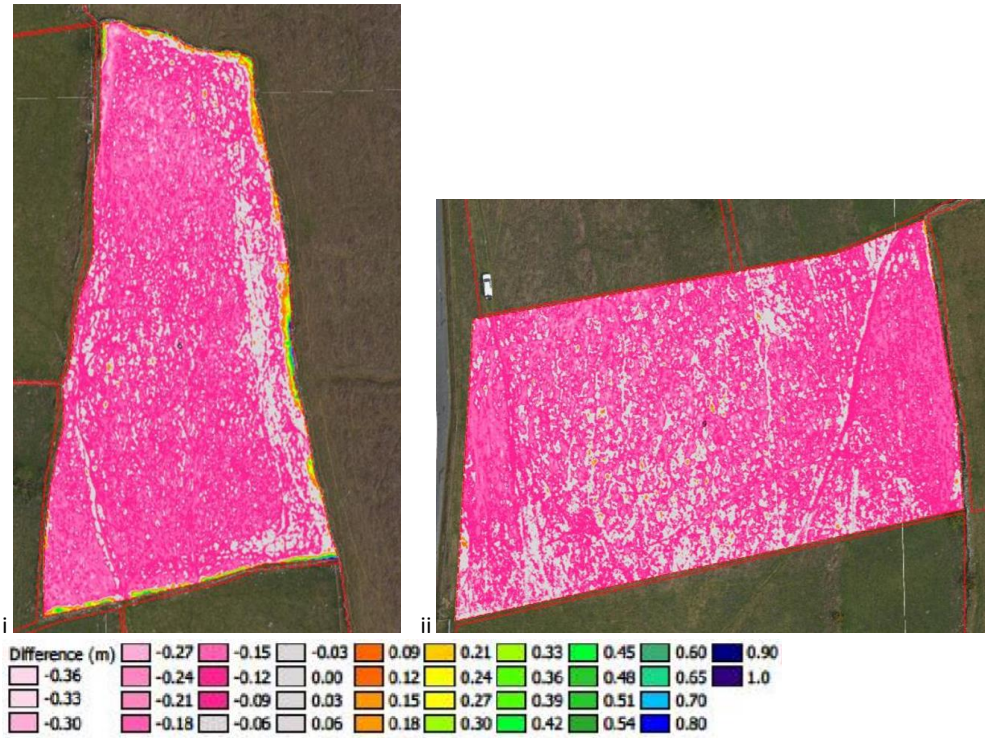


Figure 84. 2016-2019 height change (m) maps for Liming plots, Challacombe Farm, Devon (i) plot 6, (ii) plot 9. Not to scale

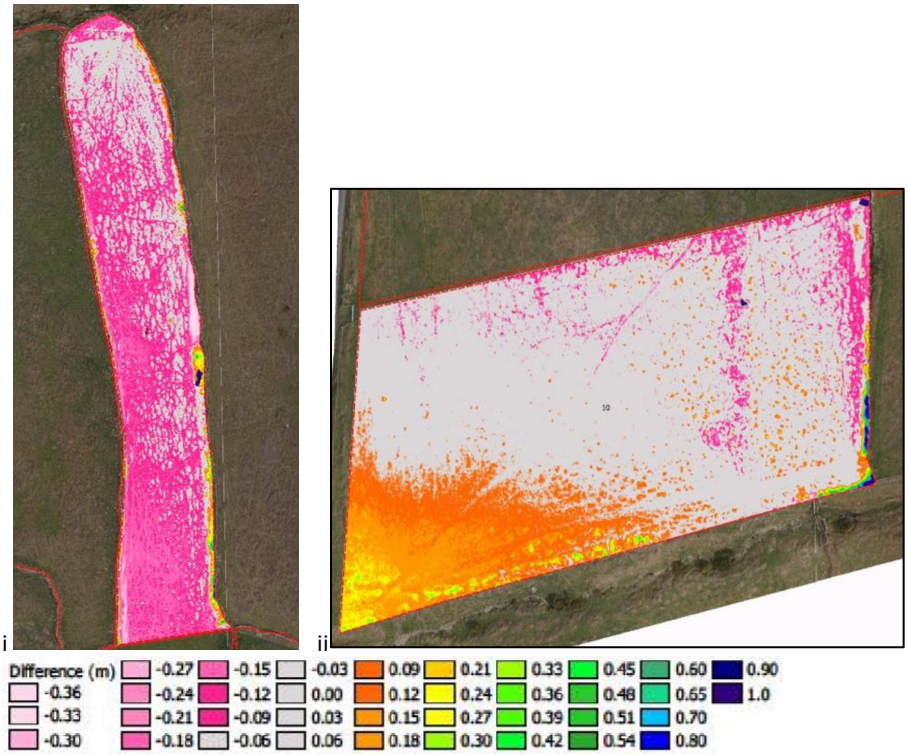


Figure 85. 2016-2019 height change (m) maps for Cut plots, Challacombe Farm, Devon (i) plot 2, (ii) plot 10. Not to scale

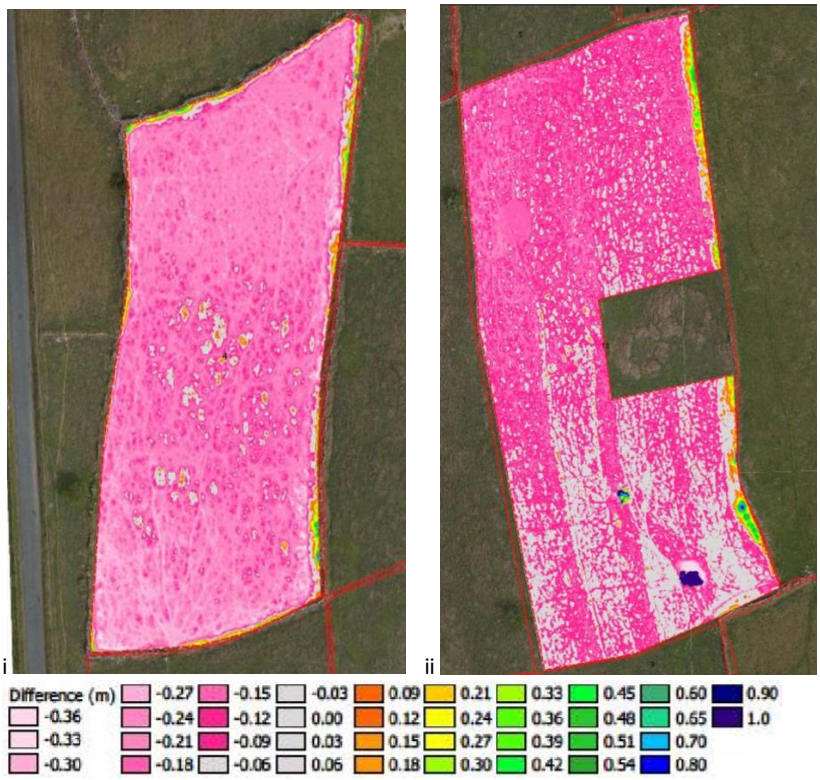


Figure 86. 2016-2019 height change (m) maps for Bash plots, Challacombe Farm, Devon (i) plot 4, (ii) plot 11. Not to scale

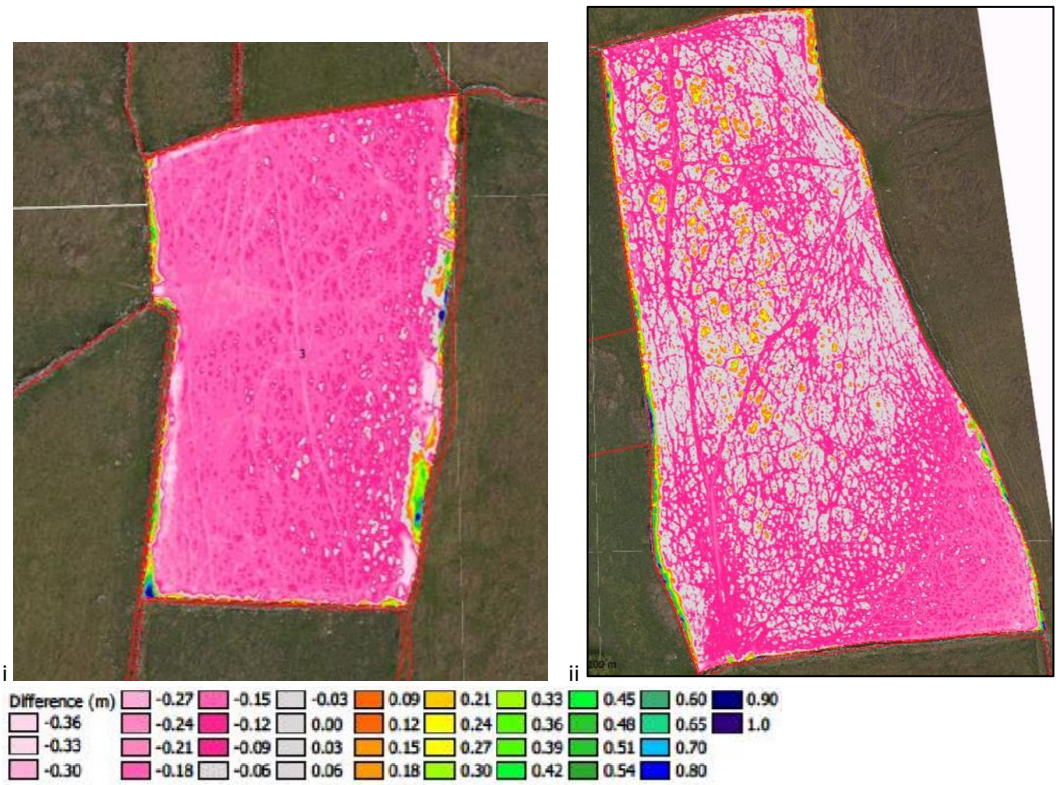
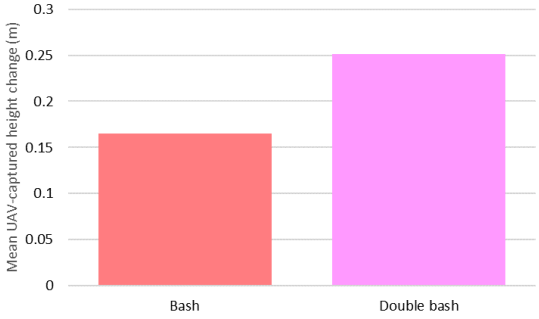


Figure 87. 2016-2019 height change (m) maps for Double-bash plots, Challacombe Farm, Devon (i) plot 3, (ii) plot 7. Not to scale

Figure 88, below shows the mean (of plot means) UAV-measured changes in ground height 2016-2019, split by four sites/blocks of plots measured by different flights at Ingram Farm, Northumberland (88i-88iii) and Challacombe Farm, Devon (88iv). Apparent differences in height vary between sites from positive to negative, irrespective of treatment.

i



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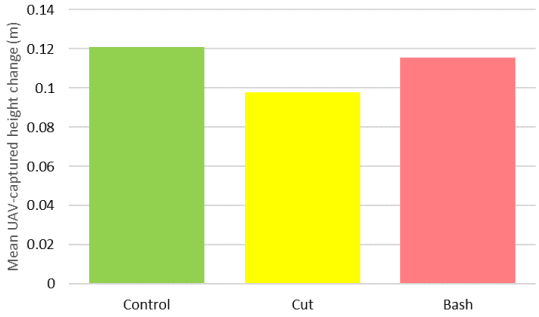

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iv

Figure 88. 2016-2019 UAV-measured mean land height change (m) by treatment (i) Ewe Hill lower plots, Ingram Farm, Northumberland, (ii) Ewe Hill upper plots, Ingram Farm, Northumberland, (iii) Wether Hill, Ingram Farm, Northumberland & (iv) physical/liming treatments, Challacombe Farm, Devon

Figure 89, below shows the mean (of plot means) UAV-recorded changes in ground height 2016-2019, split by blocks of plots measured by three separate flights at Ingram Farm, Northumberland. Each block was significantly different from the other; Wether Hill – Upper plots, Ewe Hill ($P < 0.01$), all other pairs $P < 0.001$.

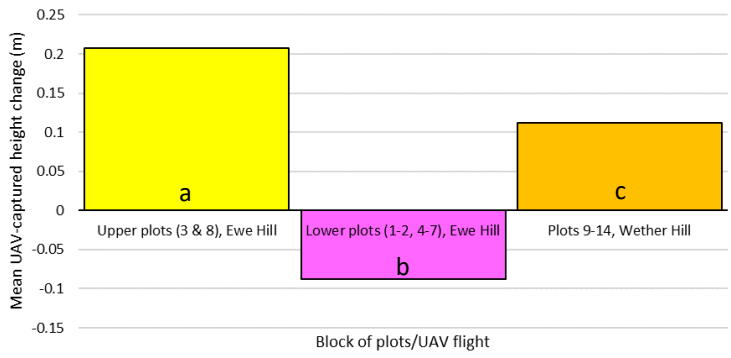


Figure 89. 2016-2019 UAV-measured mean land height change (m) by block of plots/UAV flight, Ingram Farm, Northumberland

3.4.5 COMPARISON OF GROUND-BASED ASSESSMENTS OF DAMAGE AND DISPLACEMENT VS UAV-RECORDED TERRAIN HEIGHT CHANGE ASSESSMENTS AT INGRAM FARM, NORTHUMBERLAND & CHALLACOMBE FARM, DEVON

In order to establish whether there was a relationship between two of the ground-based measures of damage to the historic environment, the Ingram Farm 2019 mean (of quadrats) percentage disturbed ground per plot was compared with the 2019 mean displacement scores for the concrete cylinders in that plot. There was a reasonably strong positive correlation (R^2 = 0.67, figure 90, below), although none of the quadrats in plots on Ewe Hill or plot 14 on Wether Hill contained disturbed ground.

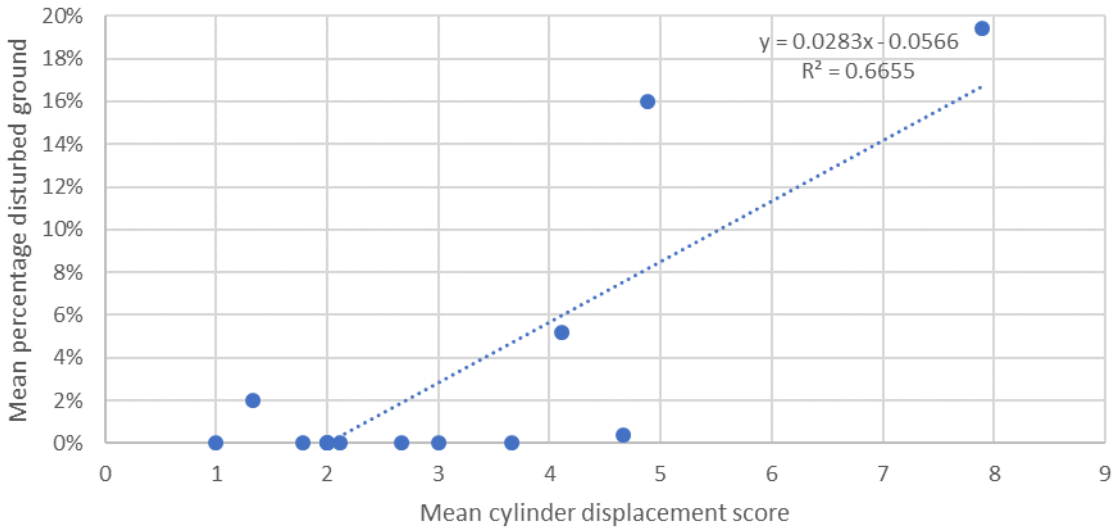


Figure 90. Linear regression of 2019 mean cylinder displacement score vs. 2019 mean percentage disturbed ground (measured by quadrats), Ingram Farm, Northumberland

At Ingram Farm there were very weak positive correlations between quadrat-measured 2019 percentage disturbed ground vs 2016-2019 UAV-recorded height change mean (R^2 = 0.13) and 2016-2019 mean cylinder displacement score vs 2016-2019 UAV-recorded height change mean (R^2 = 0.1). In order to explore the possibility of a site-specific relationship between the two ground-based measures of damage to the historic environment, regression models were fitted separately for Wether Hill and Ewe Hill.

The quadrat-measured disturbed ground on Ewe Hill was zero, so no model was fitted, but there was a reasonably strong positive correlation between mean change in ground height and cover of disturbed ground on Wether Hill (R^2 = 0.63, figure 91, below). There was also a positive correlation for Wether Hill, between mean cylinder displacement score per plot and mean change in ground height per plot (R^2 = 0.44, figure 92i, below). This was not so for the plots on Ewe Hill, where there was only a very weak negative correlation (R^2 = 0.009, figure 92i, below).

The physical/liming treatment plots at Challacombe Farm saw a positive correlation between mean cylinder displacement score per plot and mean change in ground height per plot (R^2 = 0.36, figure 92ii, below).

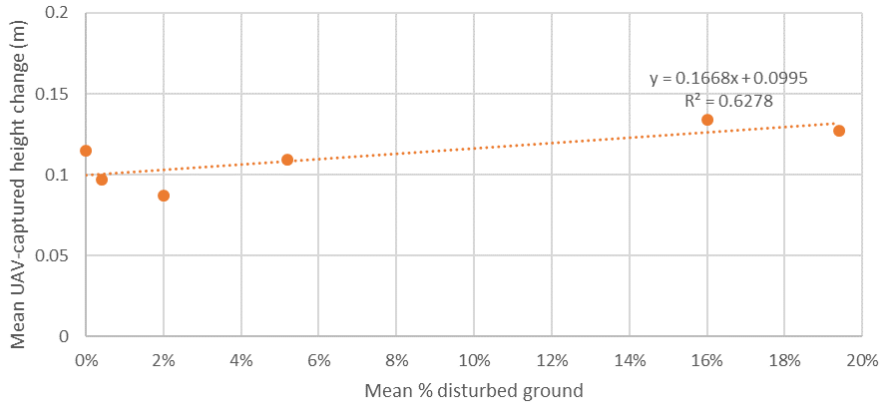
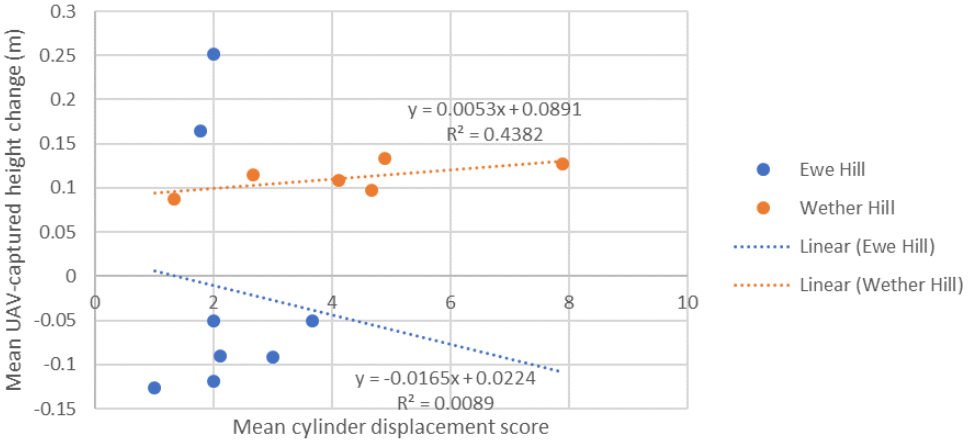


Figure 91. Linear regression of 2019 mean disturbed ground cover (measured by quadrat) vs. 2016-2019 height change (metres) measured by UAV, Wether Hill, Ingram Farm, Northumberland



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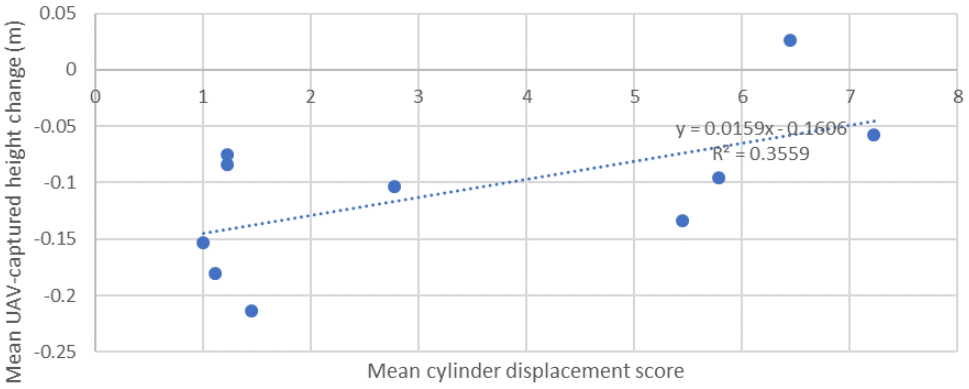

ii

Figure 92. Linear regression of mean cylinder displacement score vs. 2016-2019 height change (metres) measured by UAV, split according to treatment location at (i) Ingram Farm, Northumberland & (ii) Challacombe Farm, Devon

4. DISCUSSION

4.1 *THE VEGETATION SURVEY AND RESPONSES TO BRACKEN CONTROL TREATMENTS*

4.1.1 VEGETATION SURVEY SETUP

This section considers several aspects of the experimental setup for the study of bracken control and vegetation dynamics. In order to broaden the evidence base beyond the previous iteration of this project, this phase was designed by Historic England to test new bracken control treatments, plus existing treatments at an additional site. This means like with like comparisons are often not possible, with treatments having been started at different times and run for different periods of time. However, with a cautionary approach to interpretation of the data, there is valuable information to be gleaned about how bracken control techniques compare with one-another.

Care with interpretation of findings from Ingram Farm, Northumberland was also required because of the interaction effect between cattle foddering and the mechanical treatments at. Caution should be observed when considering quantitative effects of bracken control treatments at Ingram Farm. In terms of the general interpretation of findings, such as relative differences of treatment responses, the interaction effect is not considered to be problematic, as similar trends have been observed at Challacombe Farm and when the treatments have been analysed on a univariate basis.

There were several 'jumps' in species cover data from Ingram Farm between 2014; the end of the first phase of the project, and 2016; the start of this phase of the research. Anecdotally, recorder differences are commonplace with quadrat data, but with the addition of a years' gap in data collection, the picture is slightly more complicated. Although apparent differences due to recorder are visible in some of the figures shown in this report, they are not a cause for concern given that the analyses of the 2016 Ingram Farm data did not contradict the findings from the previous research.

Analysis of the baseline data from the plots established in 2016 at Ingram Farm indicated that most attributes of the new plots were comparable with the existing Control plots, as intended. The exception to this was bracken *cover* (but not other measures), which was significantly higher in the Controls compared with the newly established plots. This was not considered to be cause for concern given that there was much greater variation in the vegetation composition between plots established in 2011.

In 2018 there was a useful demonstration of the impact of the legal requirement to protect ground-nesting birds when applying the first bashing of the Double-bash treatment. Nesting activity was detected during a bird survey, meaning that the first bash of Double-bash plot 4 at Ingram Farm had to be delayed by two weeks to allow birds to fledge from two nests. In addition to the delayed bashing, an exclusion zone around the nests was not bashed at all at on the first bash date. This resulted in visibly greater cover of bracken in the plot compared with Double-bash plot 8, apparent from the GPS-mapping of bracken with 100% cover and a vigour score of 7 or above. The higher bracken cover in the plot did not translate to the vegetation survey by quadrat transect; there were no statistically significant differences in the various measures of bracken (cover, height, frond density) between the two Double-bash plots. This is because the transect did not pass through the areas of the plot that were left standing on the first bash date.

The Fawdon and Challacombe sites had a high cover of bluebells (*Hyacinthoides non-scripta*) early in the year, which was not captured by the July-August quadrat data collection. Observations made during the concrete cylinder assessments point to a considerable, negative impact of the mechanical and chemical treatments on cover of bluebells. These can be seen in photographs taken following several years of treatment (see figure 93, below). The July-August dates for annual collection of vegetation data were essential for understanding how bracken control techniques affected the bracken and much of the understorey, so it is unfortunate that bluebells at those two sites were not measured at their peak. It should be noted though, that bracken control may have a negative impact on cover of bluebells, which are a protected species.

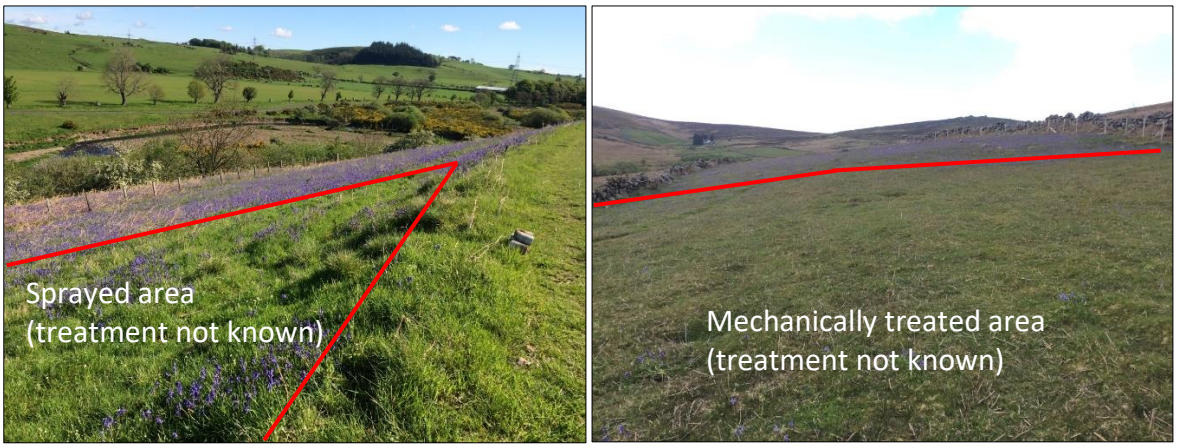

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Figure 93. Photographs showing differences in cover of bluebells (*Hyacinthoides non-scripta*) between sprayed plots at (i) Fawdon Farm, Northumberland and (ii) mechanically treated plots at Challacombe Farm, Devon

4.1.2 Assessments of GPS and UAV-based methods of bracken cover assessments at Ingram Farm, Northumberland

The GPS-based assessment of bracken cover at Ingram Farm was restrictive in terms of its ability to capture total bracken cover and extent. Prior to the first mapping exercise in 2016, it was agreed that detailed mapping of all bracken would not be possible, so the fieldwork focussed on 100% cover with a vigour score of 7 or above. Even so, mapping in the field was challenging, and has likely resulted in small patches of full-cover or low cover of bracken having been missed. Tracing the edges of the dense bracken stands usually produced several polygons which overlapped, and this required intensive post-processing. In spite of this, the GPS-mapped data *are* indicative of relative bracken cover between plots.

The mean Normalised Difference Vegetation Index (NDVI) scores were higher on Wether Hill than on Ewe Hill, often irrespective of the cover measured on the ground by quadrats or mapping by GPS. The analysis of relationships between site (hill *and* block of plots) showed that the way NDVI scores related to the bracken cover measured on the ground was site and/or flight-specific. Within each site/flight there were strong positive correlations between NDVI mean scores and bracken cover measured by GPS or quadrats. This is encouraging for possible future measurement of bracken cover by UAV, but it is important to note that the site/flight specificity of the relationship between NDVI scores and ground-measured cover means that ground-truthing will be essential if NDVI data are to be used in future for assessing bracken cover and vigour.

4.1.3 VEGETATION DYNAMICS IN RESPONSE TO BRACKEN CONTROL TECHNIQUES

Throughout the project there was year-to-year variation in the cover of bracken and the understorey species which cannot be attributed to the treatments directly. This was evident from the temporal variation observed in the Control plots. Environmental factors are likely to underlie some of this variation, for example the prolonged spell of hot and dry weather in early summer 2018, which affected the vegetation composition that year, with visibly high levels of scorched grass and signs of early senescence in the bracken on many plots, leading to lower cover scores in the vegetation survey.

After the four or nine years of treatments, variation in the effectiveness of different bracken control techniques has become possible to discern, albeit with some caution about the extent of reduction in bracken. The picture is not straightforward, given the short duration of the experiment at the newly established sites and plots compared with the nine-year duration of most plots at Ingram Farm. In particular, the Double-bash treatment, which despite the short duration of the experiment has started to have an effect on the bracken and understorey.

The effects of each bracken control treatment (and chemical control methods collectively) on the bracken and understorey are considered below.

Double-bashing

Double-bashing looks to be especially promising as a bracken control technique, with results at Challacombe Farm comparable with the Cut treatment. The Double-bash treatment at Ingram Farm resulted in significantly lower bracken vigour than the Control after four years, but not lower vigour than the Bash plot established in 2016. The experimental duration and requirement for a baseline for bracken vigour meant that the Double-bash plots were only bashed twice annually for two of the years. Nonetheless it looks to be far more effective than the Single-bash treatment, although there is no direct comparison of the Cut vs. Double-bash treatments at Ingram Farm. Anecdotally, damaging bracken fronds by trampling soon after emergence is believed to be more effective than later in the growing season. The first bash in the Double-bash treatment is comparable to trampling of recently emerged fronds of bracken, so it is possible that the early bashing been instrumental in reducing bracken vigour. However, this cannot be proven as there was no early Single-bash treatment.

Single-bashing

In general, by the end of the experiment there was no impact of the Single-bash treatment on bracken compared with the Control. The two exceptions to this were a reduction in mean frond height at Ingram Farm in the Single-bash plot established in 2016, and significantly *higher* frond density in the Single-bash treatment at Challacombe Farm. Otherwise, there was no impact at either site on bracken cover, frond density and frond height, and consequently no impact on bracken vigour.

There was however, a significant, positive response in understorey cover and species richness in the Single-bash treatment compared with the Control at the Ingram Farm plots established in 2011 and Challacombe Farm plots established in 2016. Species richness also increased in the Single-bash treatment plot established in 2016 at Ingram Farm. Understorey cover and species richness in the Single-bash treatments did not differ significantly from the Cut or Double-bash treatments.

Cutting

The Cut treatment at Ingram Farm had the lowest bracken cover, frond height, frond density and bracken vigour scores compared with the Ingram Bash treatment and Control. By 2019, following nine years of treatment, the Cut plots at Ingram Farm contained large tracts which were either bracken-free or had a very low density of bracken fronds (see figure 94, below). By 2019, but after just four years of cutting, the plots at Challacombe Farm also resulted in significantly lower bracken vigour compared with the Control, Single-bash and Liming treatments, but not the Double-bash treatment.

Unlike at Ingram Farm after the first four years of treatment, Frond density in the Cut treatment at Challacombe Farm was not significantly different from the Control. This maintenance of frond density where other measures of bracken fell corresponds with the Single-bash treatment's *increased* frond density at Challacombe Farm.

The Cut treatment, like the Single-bash treatment also saw greater species diversity and understorey cover than the Control by 2019.

Figure 94. Photograph showing the low-density bracken in a Cut treatment plot on Ewe Hill, Ingram Farm, Northumberland

Liming

The Liming treatment at Challacombe Farm did not have any discernible impact on the vegetation dynamics, which were effectively the same as the Control. This is not surprising given that liming bracken covered sites is generally accompanied by other forms of treatment and applied in order to assist the establishment of an understorey sward (SEARS, 2008).

Winter cattle foddering

The winter cattle foddering treatment on Wether Hill at Ingram Farm proved very effective at reducing bracken cover, frond height and consequently, bracken vigour compared with the Ewe Hill plots, where no winter foddering took place. There was also a positive response in understorey cover, although not species diversity. The 2016-2019 ground-based bracken mapping exercise indicates very well, the extent of bracken control by foddering. The bales were spread out on the upper parts of the plots on Wether Hill, which are flatter and more accessible by tractor, and it is the upper parts of the plots which have no bracken of vigour score 7+ or 100% cover.

Chemical control

Chemical treatments generally had a significant impact on the cover, height and frond density of bracken, with a corresponding positive response in understorey cover. Some treatments appear to have had a greater impact than others, although the picture was not consistent between the Fawdon Farm and Challacombe Farm sites. Amidosulfuron 1N was most effective at Challacombe Farm, but this was not the case at Fawdon Farm, where there no treatment was any more effective than another. In addition, understorey cover at Fawdon Farm had a higher mean in all chemical treatments compared with the Control, although this was not a statistically significant difference by the end of the trial.

The siting of chemical and physical bracken control trials together at Challacombe Farm allowed direct comparisons between the treatments providing interesting insight into the short-term effectiveness of these methods of control at the site.

By 2019 the Amidosulfuron 1N treated plots at Challacombe Farm had significantly lower *bracken cover* than all of the physical and the Liming treatments. However, bracken cover in the Cut treatment was not significantly different from any of the other chemical treatments. Bracken cover in the Double-bash treatment was not significantly different from the Asulox 1N treatment. Otherwise, bracken cover was significantly lower in all other chemical treatments compared with the physical treatments, Liming treatment and Control.

In general, by 2019, bracken *frond density* was significantly lower than the Control in the chemical treatments and higher in the physical (not Liming) treatments. The exception to this was Asulox 1N, which although having a lower mean frond density, was not significantly lower than the Control.

By 2019, bracken *frond height* was significantly lower in the Cut and Double-bash treatments than the chemical treatments, significantly higher in the Control than the chemical treatments, but none of the chemical treatments were significantly different than the Bash treatment.

With the exception of the Liming treatment, which was generally the same as the Control, there were no significant differences by 2019 in *understorey cover* between the physical treatments and chemical treatments. A similar pattern was observed for *species richness*, with the exception of the Amidosulfuron 0.5N treatment, which by 2019 had significantly higher species richness than the Cut treatment and Bash treatments. It should be noted that by 2019 there were no significant differences in species richness between any of the chemical treatments.

4.2 *DAMAGE TO THE HISTORIC ENVIRONMENT AND PROXY ARCHAEOLOGICAL REMAINS*

4.2.1 ASSESSMENTS OF DAMAGE TO THE HISTORIC ENVIRONMENT

At Ingram Farm, data measuring cover of stones, bare ground and disturbed ground was carried out to provide information about damage to the historic environment (the National Chemical Bracken Control Trials project run in parallel with this did not collect these data at Fawdon or Challacombe Farms). After nine years, there was a significantly higher percentage of disturbed ground on Wether Hill, Ingram Farm, primarily caused by cattle poaching associated with the foddering (figure 95i, below). Disturbed and bare ground was observed elsewhere in the plots at Ingram Farm, but was only recorded if it fell within a quadrat. Bare ground was particularly prevalent on the steep cultivation terraces on Ewe Hill, Ingram Farm. Where dense bracken was still present on the steep terraces; mainly in the Control and Single-bashed plots, there are large strips of bare/disturbed ground, which appear to have been used as animal scrapes. These were typically at the base of a number of terraces (figure 95ii, below). Although the extent of this was not measured, it is important to note the possible extent of damage that can occur with certain combinations of topography and shelter provided by dense bracken. It is also possible that the large areas of grassland with low bracken cover in adjacent Cut treatment plots attract livestock which subsequently utilise the terraces with a high cover of bracken for shelter.

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Figure 95. (i) Disturbed ground cause by cattle poaching on plots receiving winter fodder, Wether Hill, Ingram Farm, Northumberland & (ii) Cattle/sheep scrapes at the base of a cultivation terrace Ewe Hill, Ingram Farm, Northumberland

4.2.2 PROXY ARCHAEOLOGICAL REMAINS: EXPERIMENTAL SETUP

There was considerable variation in the topography, litter depth and density of the upper soil horizon into which the concrete cylinders were installed. This often appeared to be a function of the surrounding bracken cover, which in the case of the Ingram plots established in 2011 would itself have been a function of the bracken control treatments. The simulation of archaeological remains will on some occasions have resulted in their being inserted largely into an organic soil horizon-litter interface, especially where bracken was most vigorous. These conditions are not necessarily commensurate with the soil conditions that existing archaeological remains are to be found. As a result, the proxy remains inserted within dense bracken stands, i.e. previously untreated plots could be less stable than actual remains. This could have led to 'premature' movement of the proxy archaeological remains as a result of the mechanical treatments, before the onset of any potential stabilising effects of increased grass cover.

The installation and subsequent monitoring the concrete cylinders may have had a negative effect on bracken composition in the immediate area. Some of the intact stone grids from the previous project by Scott *el al* (2014) are surrounded by an 'island' of grass within the stand of bracken. It is thought that the trampling of bracken during annual monitoring of the stones weakened the bracken surrounding and within the grids, allowing establishment of a tight grass sward. In order to try and prevent this from happening with the concrete cylinder experiment, attention was continually paid to minimising trampling during installation and subsequent data collection.

Installation into the ground was also intended to be as low-impact as possible. The use of an auger with the same diameter as the cylinders is likely to have reduced the impact on bracken rhizomes in the vicinity, compared with the digging method employed previously. Bracken rhizomes *were* damaged during installation, but it is believed that this will not have significantly affected the intended purpose of the research. On a number of occasions, bracken fronds were observed growing in very close proximity to the cylinders (see examples in figure 96, below).

Figure 96. Examples of stipe growth in close proximity to the concrete cylinders at least one year following installation

4.2.3 COMPARISON OF UAV-BASED AND GROUND-BASED ASSESSMENTS OF DAMAGE TO THE HISTORIC ENVIRONMENT

The extent and direction of UAV-measured changes in ground height appeared to depend strongly on the site, which also meant a different UAV flight undertaken for data capture. There was strong evidence from this from the Ingram Farm data, where the plots were separated into three sets of *blocks*; one on Wether Hill and two on Ewe Hill. The measured height changes between each block were significantly different.

The UAV-recorded ground height changes *within* a plot and block correlated with the vegetation in the plots. Apparent small increases in ground height corresponded with areas having low bracken cover and high grass cover, and depending on block, moderate increases *or* decreases in height corresponding with areas of high bracken cover.

The data also appeared to have been skewed by features in the landscape that were not directly subject to the treatments. In particular at Challacombe Farm, locations of trees, shrubs and mediaeval walls had the greatest increases in measured land height. This suggests that these data did not represent ground height change, rather by some means they indicated the presence of trees, shrubs and walls, and by extension of this supposition, where present; bracken, other vegetation and bracken litter. This implies that either UAV-capture of ground height change is not suited to sites dense in bracken and/or that there were errors with the data collection or methodology used for the data collection.

4.2.4 DAMAGE AND DISPLACEMENT OF THE PROXY ARCHAEOLOGICAL REMAINS

Observations of the extent of cylinder damage and displacement revealed interesting results. All sites saw very little movement and damage in the Control plots and chemical treatment plots, although there was some damage and displacement. This is not surprising given that all cylinders were susceptible to disturbance by farm traffic and grazing livestock. It is also possible that movement could be attributed to the cylinders settling into the holes excavated by auger, especially where they had been installed in a looser substrate such as bracken litter, which was deeper on the plots with dense bracken.

There was greater cylinder displacement at Challacombe Farm, Devon compared with Ingram Farm, Northumberland, which may have arisen as a result of several factors. Differences in topography and micro-topography at each site may have played a part in the manner in which the mechanical treatments were applied. Differences in equipment used may play a part also; the bracken basher used at Ingram Farm is 1.5m wide, and heavier than the 1m wide bracken basher used at Challacombe Farm. A heavier bracken basher might be expected to cause more damage and displacement to the proxy archaeological remains. However, the wide bracken basher used at Ingram Farm was observed occasionally to result in patches of ground not being rolled in places where the surface was rough.

A number of variables affecting operation of the quad/tractor towed equipment are also likely to have affected the impact on proxy archaeological remains. The cutter blades used at Ingram Farm could be set to revolve at different speeds, their height from the ground can be adjusted, and the tractor can move at different speeds across that ground. A relatively low cutting speed was used at Ingram Farm in order to reduce the likelihood of damage to the blades (and therefore objects on the ground), which also had an impact on the intensity of the bracken cutting.

In 2017 it was decided that a second pass of the bracken basher would be carried out on the first bash of the Double-bash plots at Challacombe Farm. This was undertaken in order to ensure that the smaller, springier bracken was flattened also. It is not unreasonable to expect such an activity to take place in order to effect better control of bracken, but in doing this one might expect a doubling too of the chance of displacement and damage to the proxy archaeological remains.

The relatively large extent of micro-scale movements of concrete cylinders in the Liming treatment at Challacombe Farm was comparable to that in the Cut and Double-bash treatments. However, cylinders in the Liming plots did not experience the same, high levels of larger scale displacement and damage seen in the Cut and Double-bash treatments at Challacombe Farm.

The absence of damage and minimal displacement was typical for cylinders in the chemical treatments and Controls at Fawdon and Challacombe farms. There was one exception in a Control plot at Challacombe Farm, but the presence of a sheep trod through that plot, close to the grid of cylinders suggests that sheep traffic caused the displacement.

In the mechanical treatments the nature of cylinder damage and displacement could generally be attributed to the method of bracken control as follows: Trampling by cattle caused significant displacement but not damage. Cutting, bashing and double-bashing caused displacement *and* damage. However, damage measured and observed in the cut plots suggests that cutting can lead to either a high level of displacement and damage to a cylinder or no effect. The latter is likely to occur through the establishment of a tight grass sward, which results in the cylinder being protected and sometimes partially covered by the developing sward. In some instances, both could occur, with cylinders having been displaced and damaged in the year following installation then bedding into their new locations surrounded by dense grass.

5. BIBLIOGRAPHY

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6. APPENDICES

6.1 ADDITIONAL FIGURES AND TABLES DESCRIBING THE VEGETATION DYNAMICS AT INGRAM, FAWDON AND CHALLACOMBE FARMS

6.1.1 *BRACKEN VIGOUR AT INGRAM FARM, NORTHUMBERLAND*

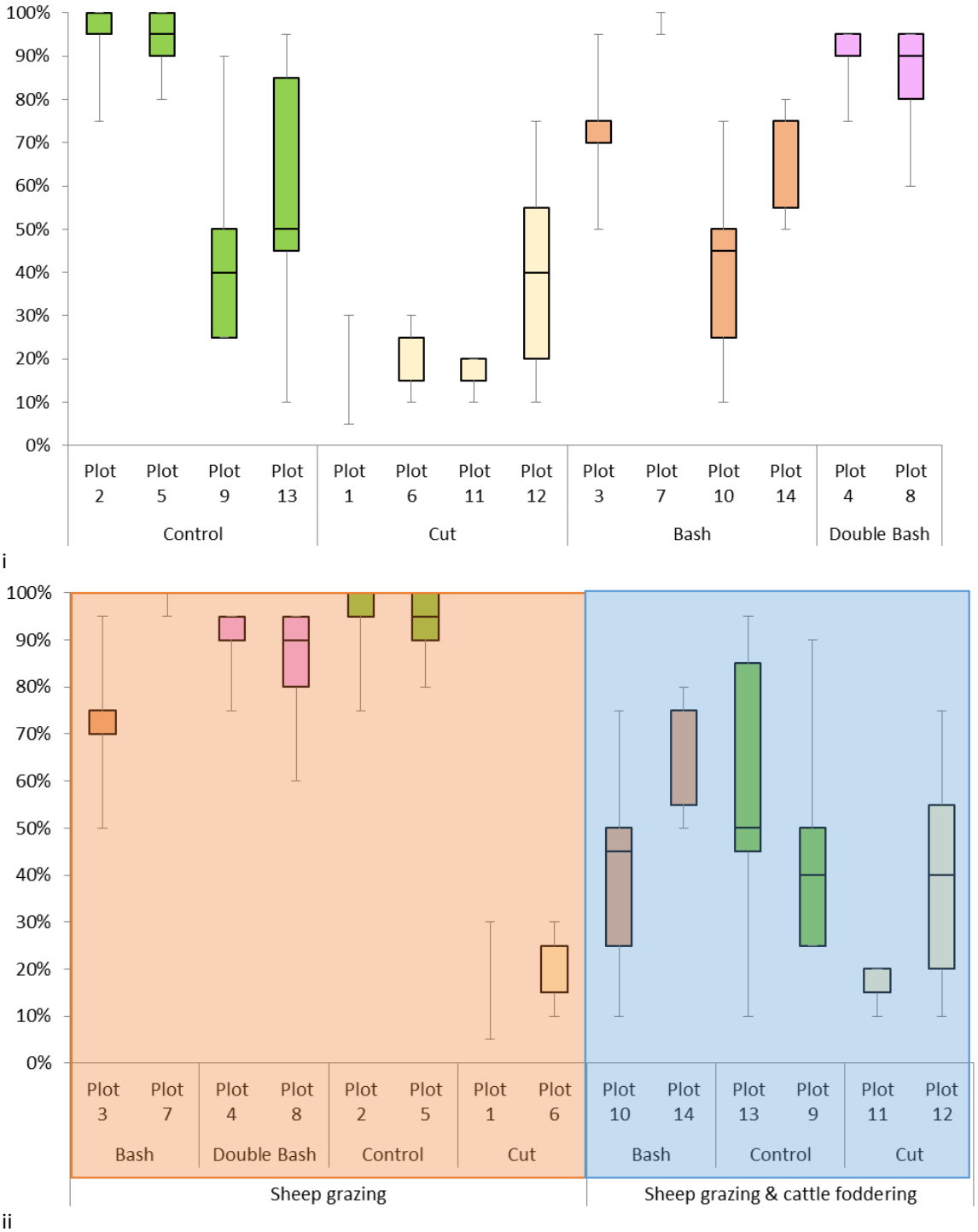
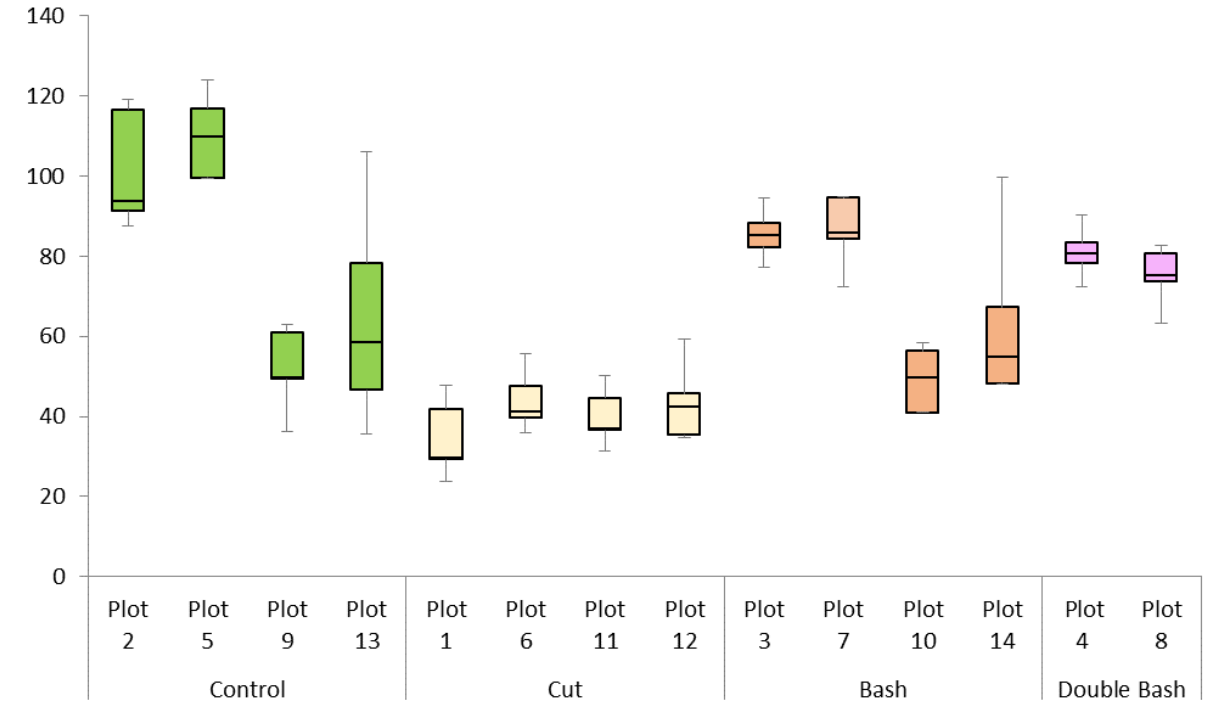


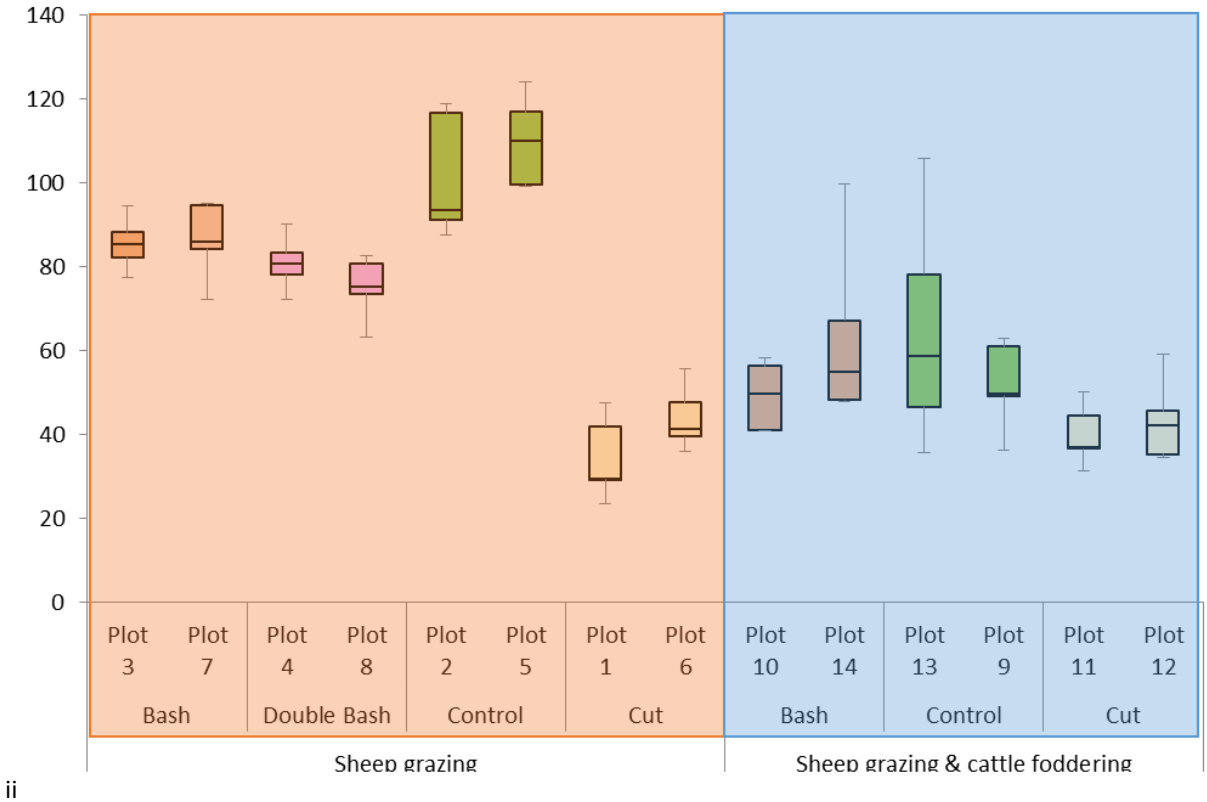
Figure 97. Median bracken cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii)

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2 3.0976  1.5488  45.250 2.11e-11 ***
Grazing      1 0.6638  0.6638  19.394 6.71e-05 ***
Plot         7 1.3451  0.1922   5.614 0.000114 ***
Residuals   44 1.5060  0.0342

Significant pairwise comparisons:
Mechanical treatment
                    diff        lwr          upr     p adj
Cut-Control        -0.5075 -0.6494006 -0.3655994 0.0000000
Single Bash-Cut     0.4725  0.3192298  0.6257702 0.0000000

Grazing treatment
                       diff        lwr        upr    p adj
Sheep/Cattle-Sheep -0.2181667 -0.3191364 -0.117197 7.85e-05
```

Table 6. ANOVA & Tukey range test on mean bracken cover 2019 (%) according to plot, mechanical treatment & grazing treatment



i

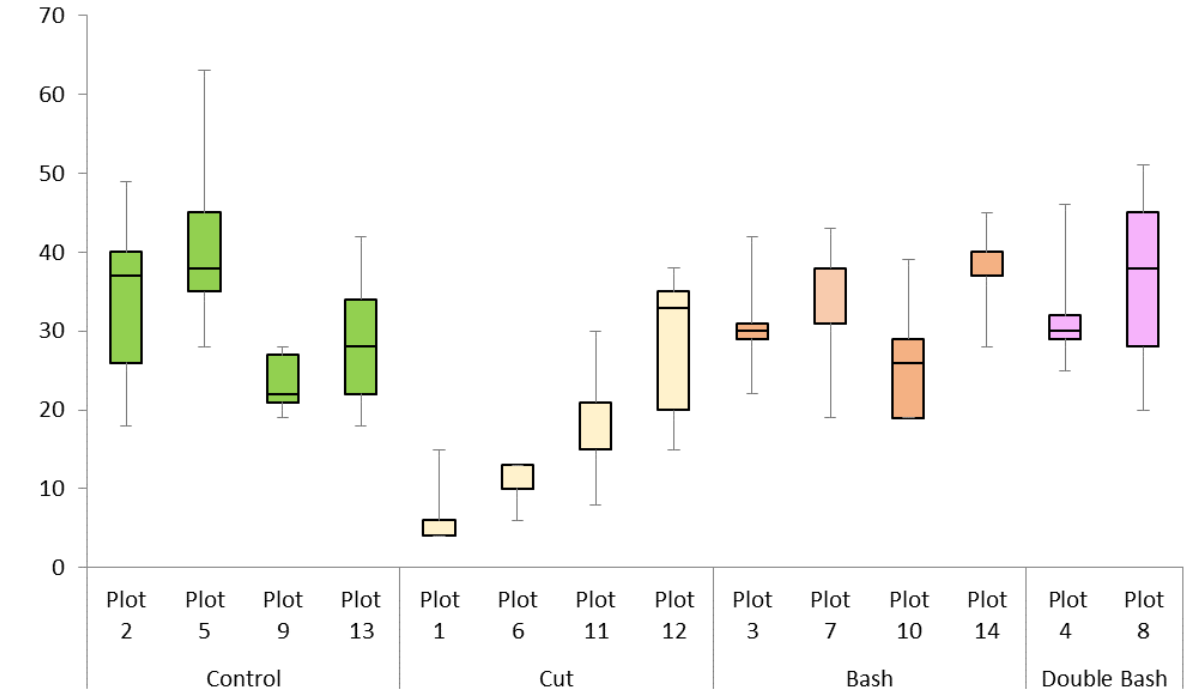


ii

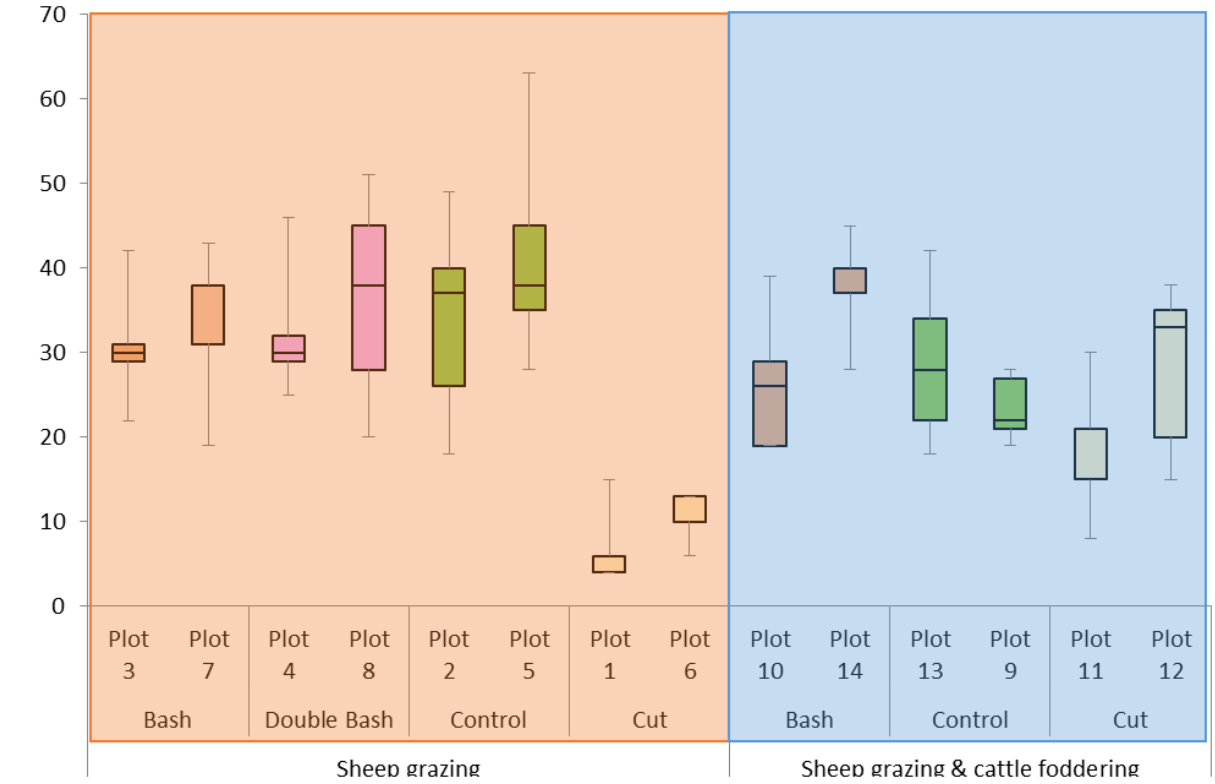
Figure 98. Median (min, Q1, Q3, max) bracken frond height 2019 (cm), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  17634    8817  44.828 2.42e-11 ***
Grazing      1   7902    7902  40.177 1.07e-07 ***
Plot         7   7736    1105   5.619 0.000113 ***
Residuals   44   8654     197

Significant pairwise comparisons:
Mechanical treatment
                       diff       lwr        upr     p adj
Cut-Control         -41.650 -52.40688 -30.893116 0.0000000
Single Bash-Control -15.695 -27.31376  -4.076237 0.0057179
Single Bash-Cut      25.955  14.33624  37.573763 0.0000071

Grazing treatment
                      diff       lwr       upr p adj
Sheep/Cattle-Sheep -23.804 -31.45809 -16.14991 1e-07
```

Table 7. ANOVA & Tukey range test on mean bracken frond height 2019 (cm) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i

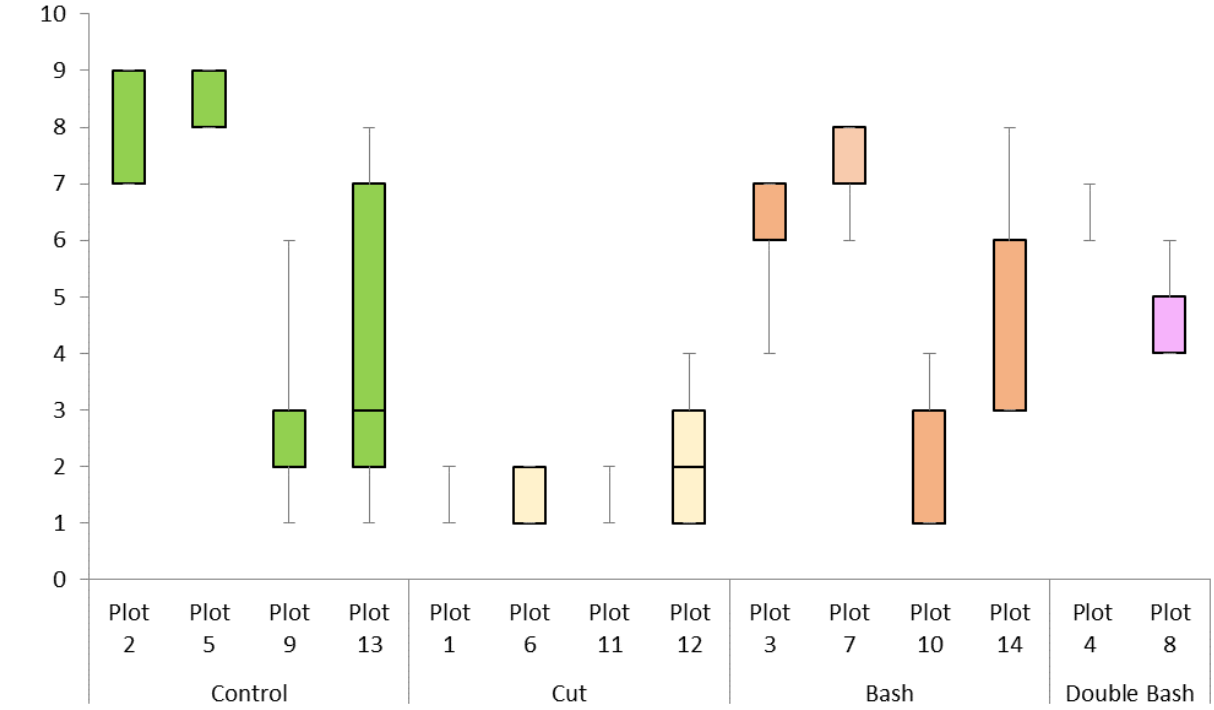


ii

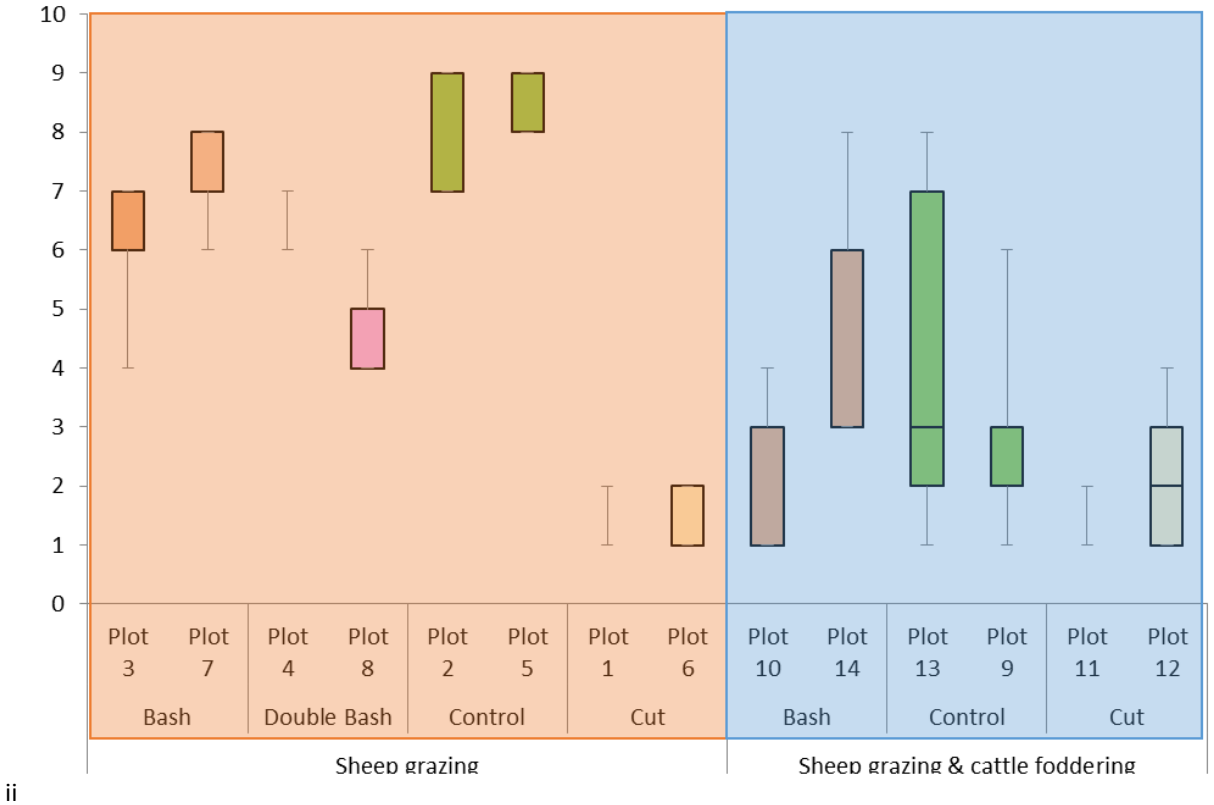
Figure 99. Median (min, Q1, Q3, max) bracken frond density 2019 (live fronds per m^2), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2   3334  1666.9  22.230 2.13e-07 ***
Grazing      1      8     7.8   0.103 0.749326
Plot         7   2616   373.7   4.984 0.000326 ***
Residuals   44   3299    75.0

Significant pairwise comparisons:
Mechanical treatment
                         diff       lwr       upr     p adj
Cut-Control         -15.9500000 -22.59165 -9.308349 0.0000018
Single Bash-Cut      16.4833333   9.30953 23.657136 0.0000042
```

Table 8. ANOVA & Tukey range test on bracken frond density 2019 (live fronds per m^2), according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i



ii

Figure 100. Median (min, Q1, Q3, max) bracken vigour 2019 (score 1-10), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
        Kruskal-Wallis rank sum test

data:  vigour by Treatment
Kruskal-Wallis chi-squared = 9.9171, df = 1, p-value =
0.001638
```

Table 9. Kruskal Wallis test of 2016 bracken vigour scores from plots established in 2011 at Ingram Farm, Northumberland, comparing bracken vigour scores between mechanical treatments & sheep grazing vs. sheep grazing with cattle foddering

i. Mechanical treatments

```
Kruskal-Wallis chi-squared = 23.374, df = 2, p-value = 8.402e-06

      Comparison          Z      P.unadj        P.adj
1 Bash - Control -0.7567938 4.491734e-01 4.491734e-01
2     Bash - Cut  3.4862142 4.899086e-04 7.348629e-04
3  Control - Cut  4.5829724 4.584125e-06 1.375237e-05
```

ii. Grazing treatments

```
Kruskal-Wallis chi-squared = 5.2807, df = 1, p-value = 0.02156
```

Table 10. Kruskal Wallis test & Dunn's post-hoc test of 2019 bracken vigour scores from plots established in 2011 at Ingram Farm, Northumberland, comparing bracken vigour scores between (i) mechanical treatments & (i) sheep grazing vs. sheep grazing with cattle foddering

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   2 0.1401 0.07005   4.798 0.0199 *
Plot         2 0.0065 0.00325   0.223 0.8024
Residuals   20 0.2920 0.01460

Significant pairwise comparisons:
                          diff        lwr        upr     p adj
Single Bash-Control     -0.205 -0.3724382 -0.03756184 0.0149943
```

Table 11. ANOVA & Tukey test on mean bracken cover (%) in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   2   4017  2008.4  20.806 1.3e-05 ***
Plot         2    260   129.8   1.344   0.283
Residuals   20   1931    96.5

Significant pairwise comparisons:
                          diff        lwr        upr     p adj
Double Bash-Control     -27.768 -38.884148 -16.651852 0.0000104
Single Bash-Control     -20.236 -33.850445  -6.621555 0.0033721
```

Table 12. ANOVA & Tukey test of mean frond height in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   2  175.7   87.87   0.734  0.492
Plot         2  192.1   96.05   0.802  0.462
Residuals   20 2394.0  119.70
```

Table 13. ANOVA & Tukey test of mean number of living bracken shoots per m^2 in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
Kruskal-Wallis chi-squared = 16.491, df = 2, p-value = 0.0002625
```

	Comparison	Z	P.unadj	P.adj
1	Bash - Control	-2.4968735	1.252936e-02	0.0187940441
2	Bash – Double-Bash	0.7224456	4.700205e-01	0.4700205319
3	Control – Double-Bash	3.9428447	8.052081e-05	0.0002415624

Table 14. Kruskal Wallis test & Dunn's post-hoc test of 2019 bracken vigour scores from new plots (3, 4 & 8) on Ewe Hill, Ingram Farm, Northumberland, comparing bracken vigour scores between mechanical treatments & plots

6.1.2 *Bracken vigour at mechanical/liming treatment plots, Challacombe Farm, Devon*

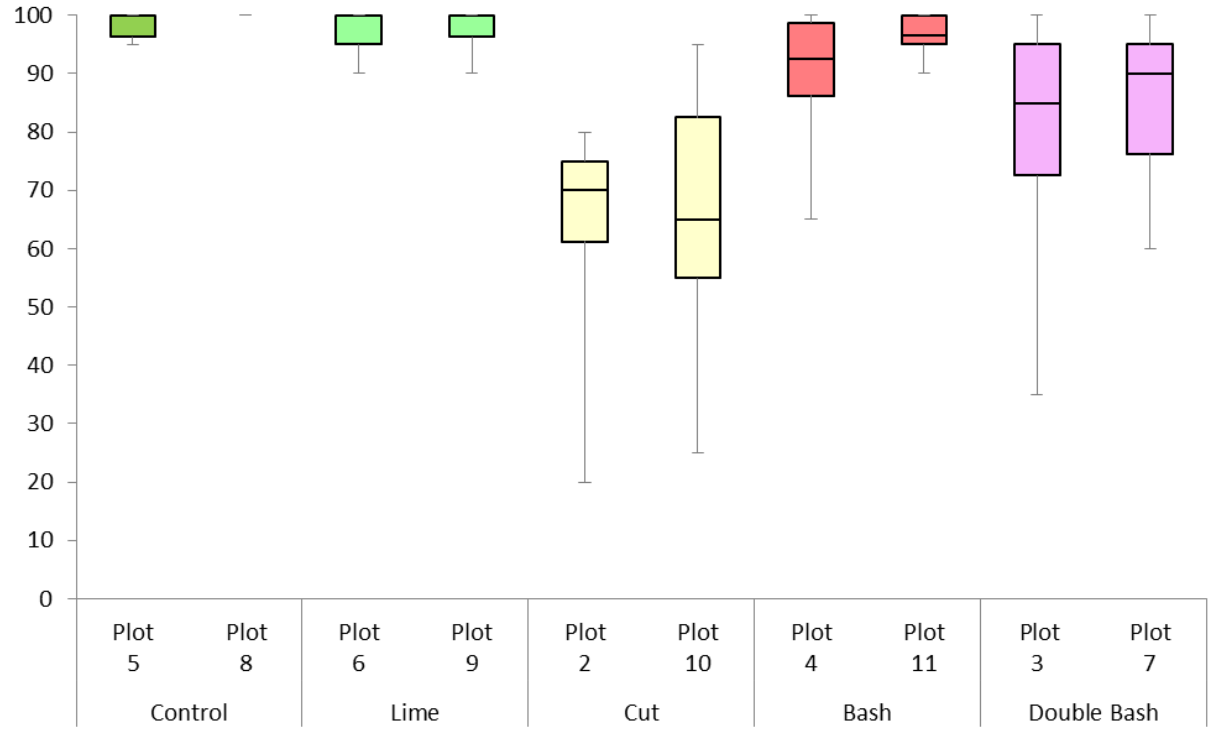


Figure 101. Median (min, Q1, Q3, max) cover (%) of bracken in mechanical/liming treatment plots at Challacombe Farm, Devon, 2019

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Mechanical	4	1.5899	0.3975	24.766	7.66e-14	***
Plot	5	0.0386	0.0077	0.481	0.79	
Residuals	90	1.4444	0.0160			

Significant pairwise comparisons:
Mechanical treatments

	diff	lwr	upr	p adj
Cut-Bash	-0.2865	-0.39802452	-0.174975477	0.0000000
Cut-Control	-0.3425	-0.45402452	-0.230975477	0.0000000
Double-bash-Control	-0.1650	-0.27652452	-0.053475477	0.0007883
Double-bash-Cut	0.1775	0.06597548	0.289024523	0.0002512
Lime-Cut	0.3200	0.20847548	0.431524523	0.0000000
Lime-Double-bash	0.1425	0.03097548	0.254024523	0.0053104

Table 15. ANOVA & Tukey test on mean bracken cover (%) 2019, comparing mechanical/liming treatments at Challacombe Farm, Devon

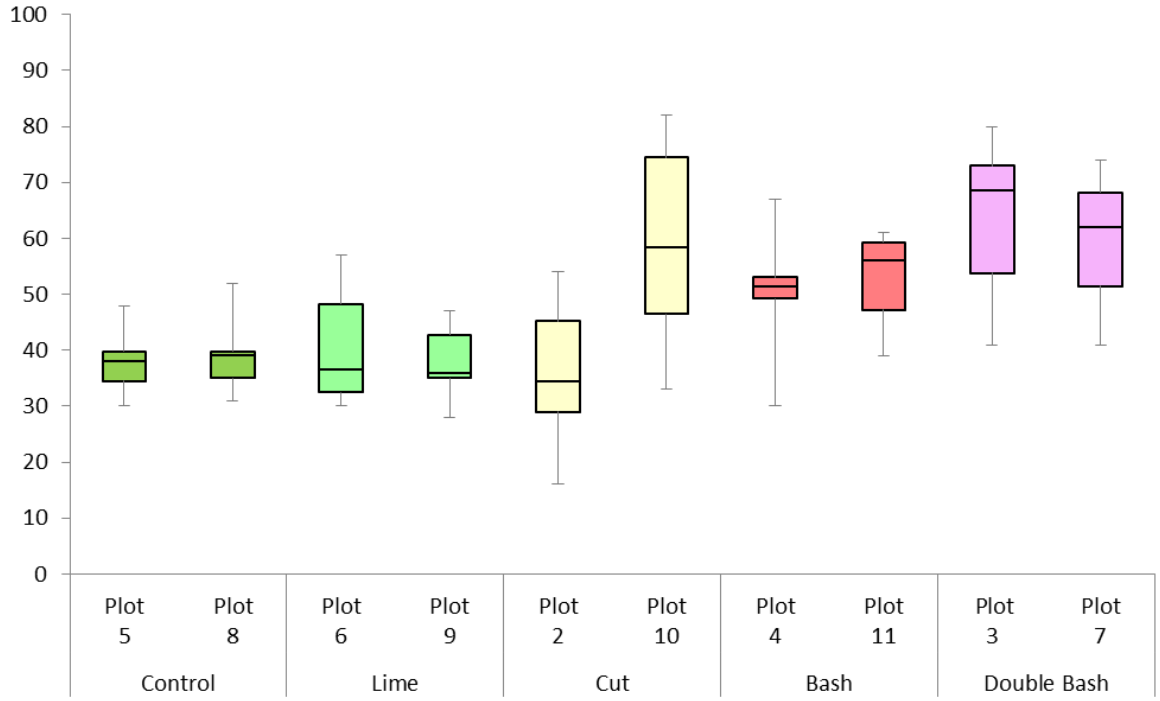


Figure 102. Median (min, Q1, Q3, max) number (± standard deviation) of living bracken shoots per m^2 in mechanical/liming treatment plots at Challacombe Farm, Devon, 2019

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   7447  1861.7  15.881 7.17e-10 ***
Plot         5   2881   576.3   4.916 0.000505 ***
Residuals   90  10551   117.2

Significant pairwise comparisons:
Mechanical treatments
                     diff         lwr         upr     p adj
Control-Bash       -13.00 -22.5315088  -3.4684912 0.0024125
Double-bash-Bash    10.10   0.5684912  19.6315088 0.0322340
Lime-Bash          -12.75 -22.2815088  -3.2184912 0.0030805
Double-bash-Control 23.10  13.5684912  32.6315088 0.0000000
Double-bash-Cut     13.95   4.4184912  23.4815088 0.0009232
Lime-Double-bash   -22.85 -32.3815088 -13.3184912 0.0000000
```

Table 16. ANOVA & Tukey test of 2019 mean number of living bracken shoots per m^2 in mechanical/liming treatment plots at Challacombe Farm, Devon

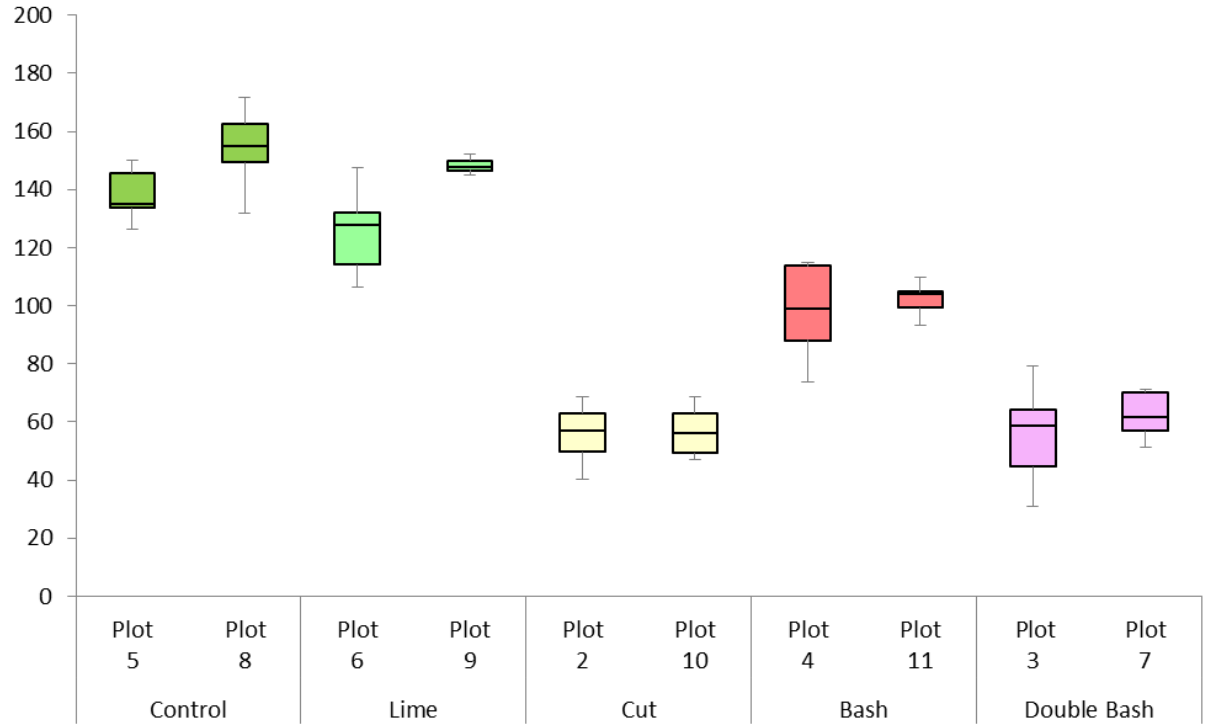


Figure 103. Median (min, Q1, Q3, max) (± standard deviation) of mean bracken frond height of tallest 10 fronds per quadrat in mechanical/liming treatment plots at Challacombe Farm, Devon, 2019

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   4 140232   35058  309.14 < 2e-16 ***
Plot         5   4156     831    7.33 8.4e-06 ***
Residuals   90  10206     113
```

```
Significant pairwise comparisons:
Mechanical treatment
                      diff        lwr         upr     p adj
Control-Bash         45.565  36.190256  54.9397437 0.0000000
Cut-Bash            -44.050 -53.424744 -34.6752563 0.0000000
Double-bash-Bash    -40.980 -50.354744 -31.6052563 0.0000000
Lime-Bash            36.300  26.925256  45.6747437 0.0000000
Cut-Control         -89.615 -98.989744 -80.2402563 0.0000000
Double-bash-Control -86.545 -95.919744 -77.1702563 0.0000000
Lime-Cut             80.350  70.975256  89.7247437 0.0000000
Lime-Double-bash     77.280  67.905256  86.6547437 0.0000000
```

Table 17. ANOVA & Tukey test of 2019 mean frond height in quadrats in mechanical/liming treatment plots at Challacombe Farm, Devon

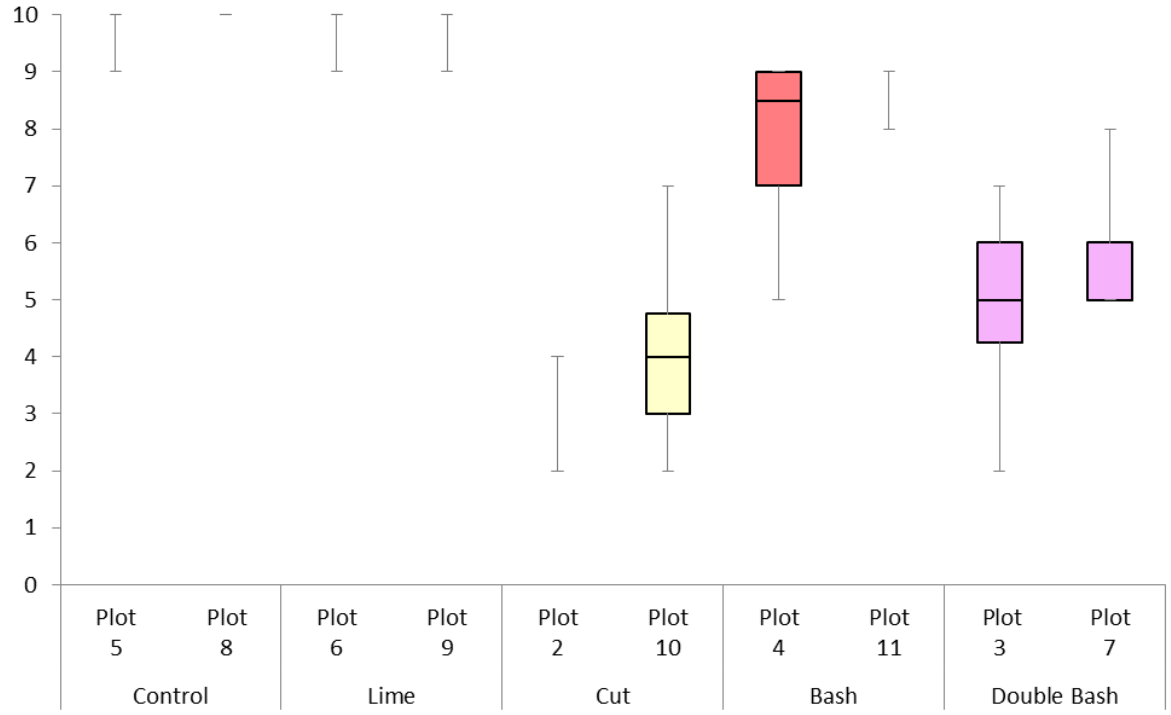


Figure 104. Median (min, Q1, Q3, max) bracken vigour score in mechanical/liming treatment plots at Challacombe Farm, Devon, 2019

```
Kruskal-Wallis chi-squared = 87.591, df = 4, p-value < 2.2e-16
```

	Comparison	Z	P.unadj	P.adj
1	Bash - Control	-3.751585	1.757202e-04	2.928669e-04
2	Bash - Cut	4.065374	4.795548e-05	9.591095e-05
3	Control - Cut	7.816959	5.411468e-15	5.411468e-14
4	Bash - Double-bash	2.421452	1.545863e-02	1.932329e-02
5	Control - Double-bash	6.173037	6.699039e-10	2.233013e-09
6	Cut - Double-bash	-1.643922	1.001924e-01	1.113248e-01
7	Bash - Lime	-2.707473	6.779769e-03	9.685384e-03
8	Control - Lime	1.044112	2.964334e-01	2.964334e-01
9	Cut - Lime	-6.772847	1.262728e-11	6.313641e-11
10	Double-bash - Lime	-5.128925	2.914016e-07	7.285041e-07

Table 18. Kruskal Wallis test & Dunn's post-hoc test of 2019 bracken vigour scores in mechanical/liming treatment plots at Challacombe Farm, Devon

6.1.3 *BRACKEN VIGOUR CHEMICAL TREATMENT PLOTS, CHALLACOMBE FARM, DEVON*

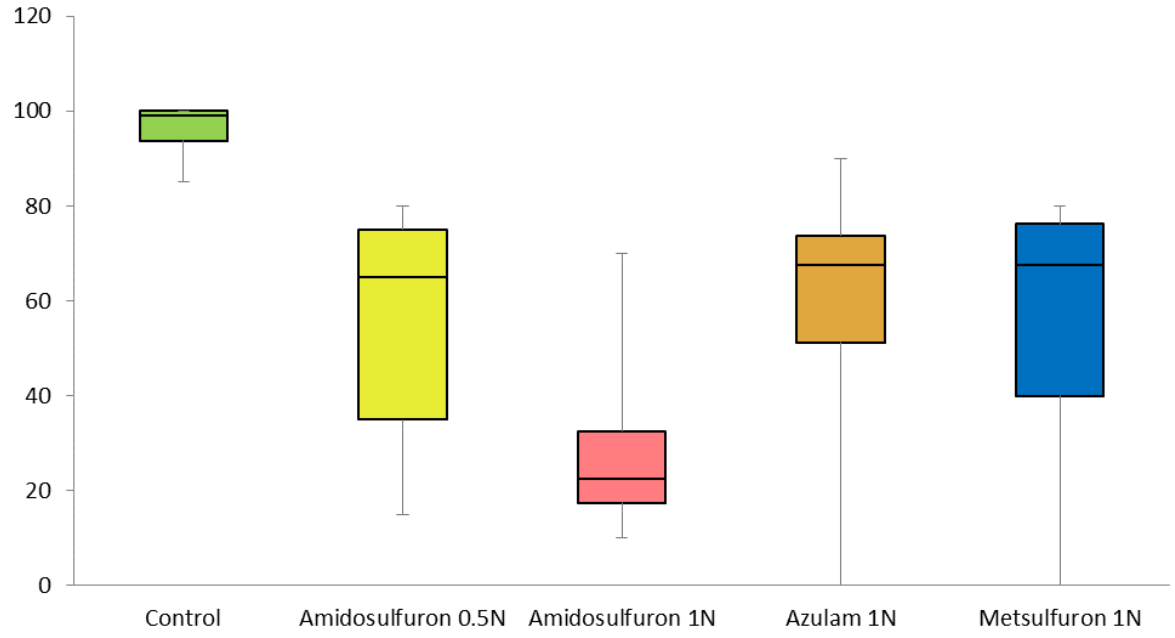


Figure 105. Median (min, Q1, Q3, max) cover (%) of bracken in chemical treatment plots at Challacombe Farm, Devon, 2019

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Chemical     4  2.850  0.7125   21.07 1.92e-10 ***
Residuals   53  1.792  0.0338

Significant pairwise comparisons:
                                          diff         lwr         upr    p adj

Amidosulfuron 1N-Amidosulfuron 0.5N -0.27916667 -0.49115282 -0.06718051 0.0042432
Control-Amidosulfuron 0.5N           0.40083333  0.18884718  0.61281949 0.0000192
Asulam 1N-Amidosulfuron 1N           0.39356061  0.17681012  0.61031109 0.0000406
Control-Amidosulfuron 1N             0.68000000  0.46801385  0.89198615 0.0000000
Metsulfuron 1N-Amidosulfuron 1N      0.33446970  0.11771921  0.55122018 0.0005617
Control-Asulam 1N                    0.28643939  0.06968891  0.50318988 0.0040795
Metsulfuron 1N-Control              -0.34553030 -0.56228079 -0.12877982 0.0003481
```

Table 19. ANOVA & Tukey test on 2019 mean bracken cover (%) in chemical treatment plots at Challacombe Farm, Devon

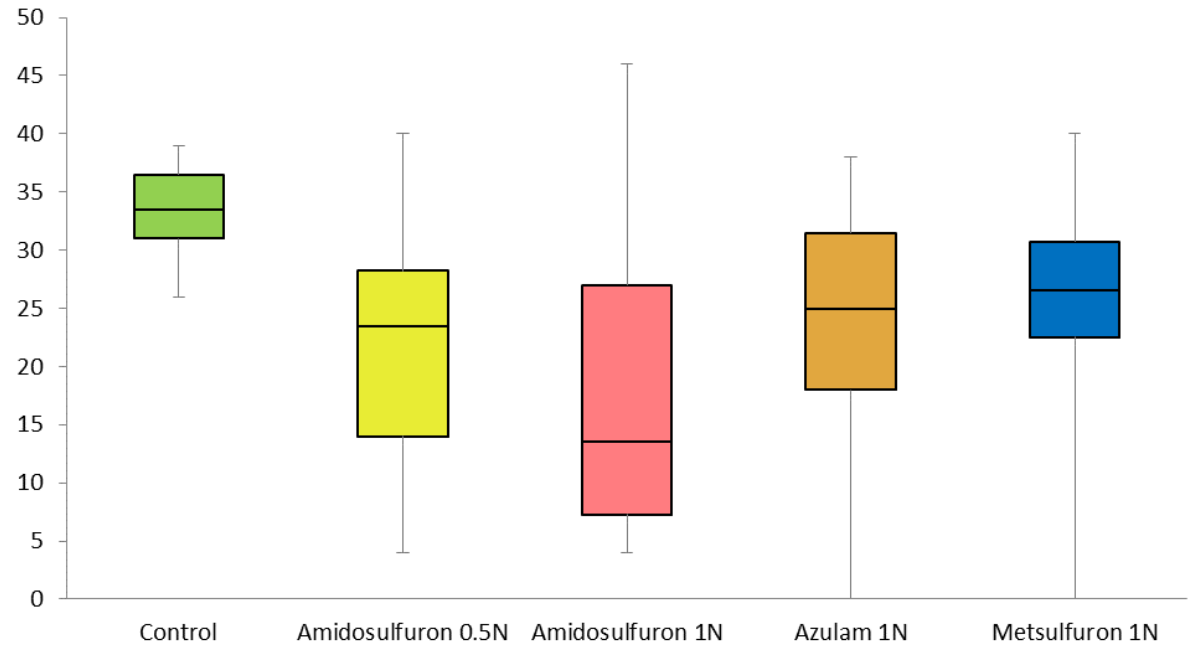


Figure 106. Median (min, Q1, Q3, max) number living bracken shoots per m^2 in chemical treatment plots at Challacombe Farm, Devon, 2019

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Chemical	4	1613	403.2	4.244	0.00471 **
Residuals	53	5035	95.0		

Significant pairwise comparisons:

	diff	lwr	upr	p adj
Control-Amidosulfuron 0.5N	11.583333	0.3463978	22.820269	0.0402731
Control-Amidosulfuron 1N	15.416667	4.1797311	26.653602	0.0026373

Table 20. ANOVA & Tukey test of 2019 mean number of living bracken shoots per m^2 in chemical treatment plots at Challacombe Farm, Devon

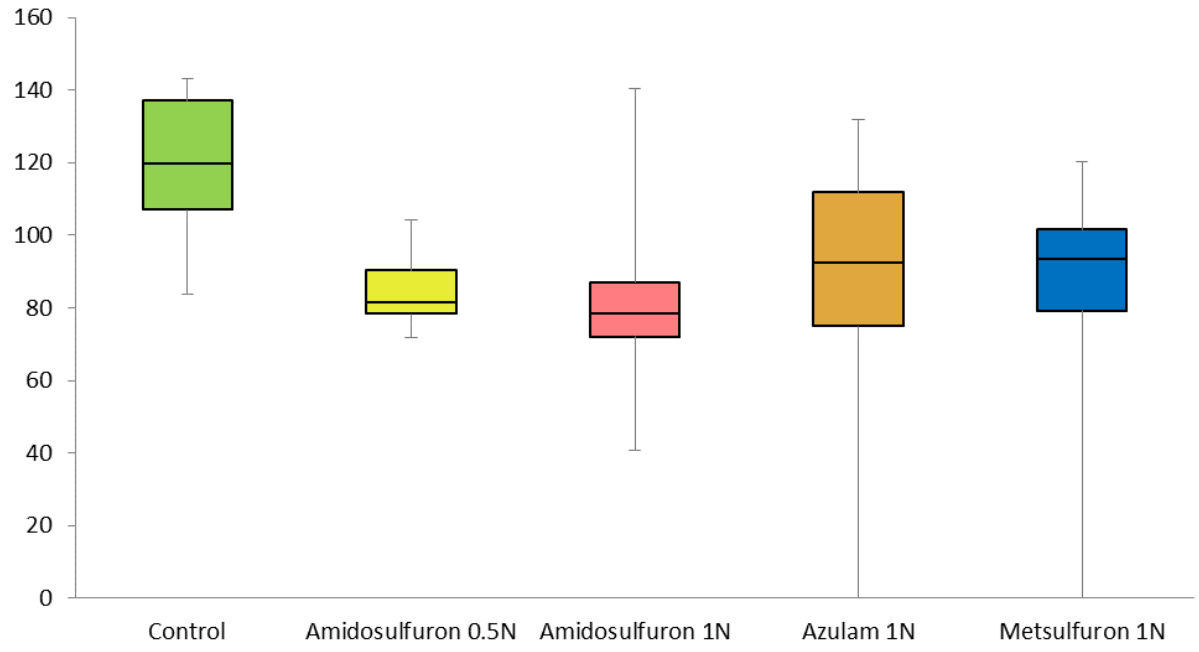


Figure 107. Median (min, Q1, Q3, max) of mean bracken frond height of tallest 5 fronds per plot in chemical treatment plots at Challacombe Farm, Devon, 2019

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	8778	2194.6	5.003	0.0017	**
Residuals	53	23247	438.6			

Significant pairwise comparisons:

	diff	lwr	upr	p adj
Control-Amidosulfuron 0.5N	32.8666667	8.722139	57.0111945	0.0028957
Control-Amidosulfuron 1N	33.1333333	8.988805	57.2778612	0.0026297

Table 21. ANOVA & Tukey test of 2019 mean frond height in quadrats in chemical treatment plots at Challacombe Farm, Devon

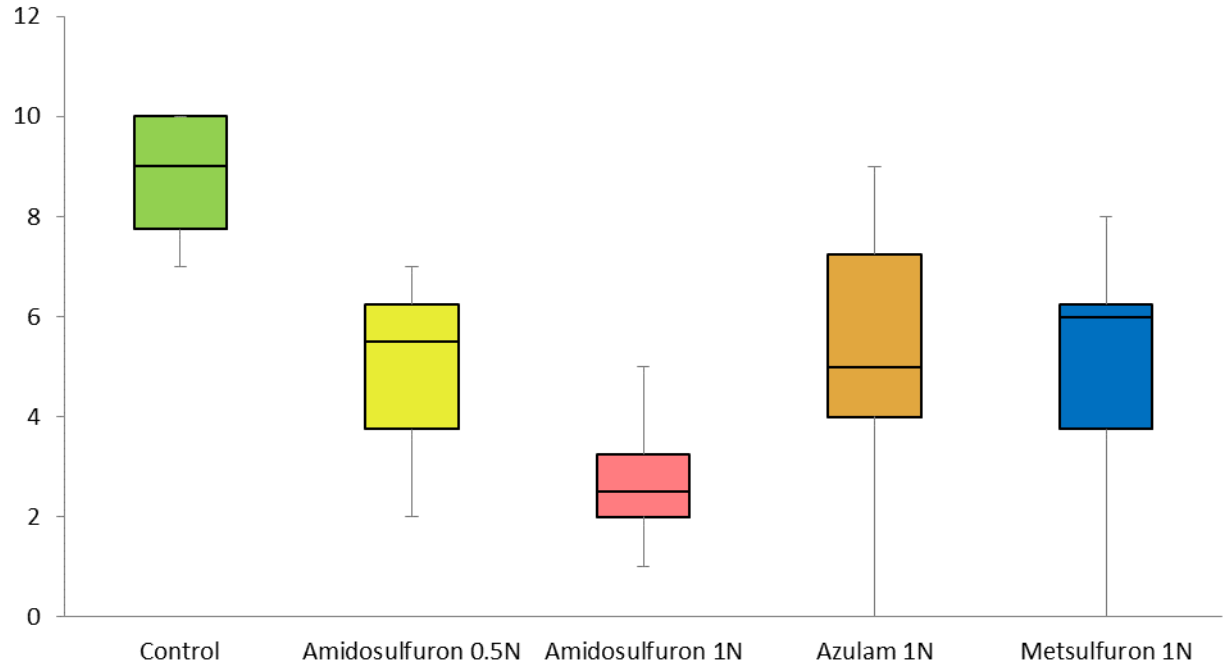


Figure 108. Median (min, Q1, Q3, max) bracken vigour score in chemical treatment plots at Challacombe Farm, Devon, 2019

Kruskal-Wallis chi-squared = 33.58, df = 4, p-value = 9.087e-07

1	AmidosulfuronOpt5N - Amidosulfuron1N	2.21922715	2.647127e-02	3.781611e-02
2	AmidosulfuronOpt5N - Asulam1N	-0.99294891	3.207349e-01	4.009186e-01
3	Amidosulfuron1N - Asulam1N	-3.16339588	1.559401e-03	3.898503e-03
4	AmidosulfuronOpt5N - Control	-3.45744823	5.453170e-04	2.726585e-03
5	Amidosulfuron1N - Control	-5.67667538	1.373377e-08	1.373377e-07
6	Asulam1N - Control	-2.38850217	1.691721e-02	3.383442e-02
7	AmidosulfuronOpt5N - Metsulfuron1N	-0.09570791	9.237526e-01	9.237526e-01
8	Amidosulfuron1N - Metsulfuron1N	-2.31493506	2.061649e-02	3.436081e-02
9	Asulam1N - Metsulfuron1N	0.89934473	3.684691e-01	4.094101e-01
10	Control - Metsulfuron1N	3.36174032	7.745292e-04	2.581764e-03

Table 22. Kruskal Wallis test & Dunn's post-hoc test of 2019 bracken vigour scores in chemical treatment plots at Challacombe Farm, Devon

6.1.4 *BRACKEN VIGOUR AT CHEMICAL TREATMENT PLOTS, FAWDON FARM, NORTHUMBERLAND*

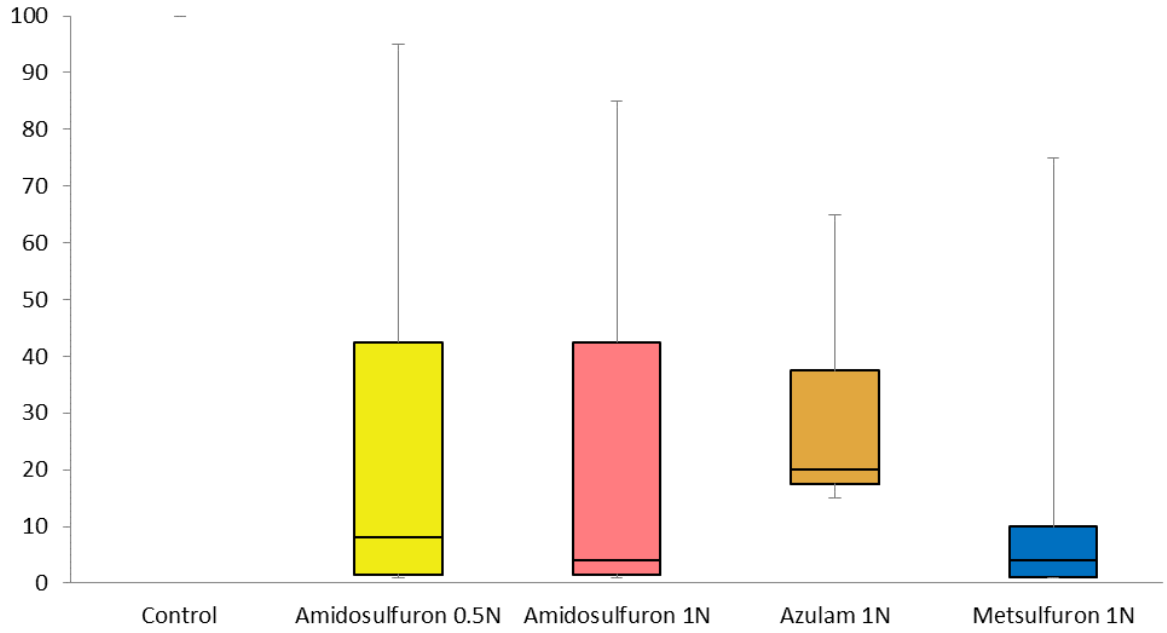


Figure 109. Median (min, Q1, Q3, max) cover (%) of bracken in chemical treatment plots at Fawdon Farm, Northumberland, 2019

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Chemical     4  2.501  0.6251   7.102 0.000444 ***
Residuals   28  2.464  0.0880

Significant pairwise comparisons:
                          diff        lwr        upr     p adj
Control-Amido 0.5N     0.75857143  0.2524560  1.2646868 0.0013617
Control-Amido 1N       0.73571429  0.2295989  1.2418297 0.0019263
Control-Asulam 1N      0.64000000  0.1338846  1.1461154 0.0079656
Metsulf 1N-Control    -0.84428571 -1.3504011 -0.3381703 0.0003652
```

Table 23. ANOVA & Tukey test on 2019 mean bracken cover (%) in chemical treatment plots at Fawdon Farm, Northumberland

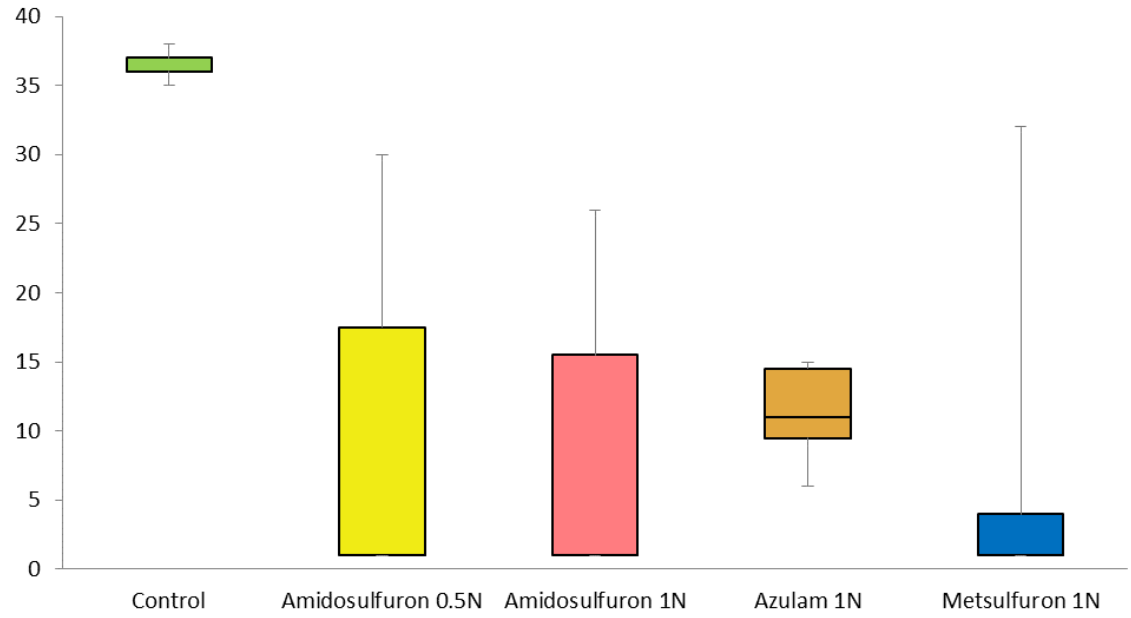


Figure 110. Median (min, Q1, Q3, max) number (± standard deviation) of living bracken shoots per m^2 in chemical treatment plots at Fawdon Farm, Northumberland, 2019

```
           Df Sum Sq Mean Sq F value   Pr(>F)
Chemical    4   3203   800.8   7.671 0.000264 ***
Residuals  28   2923   104.4

Significant pairwise comparisons:
                          diff        lwr        upr     p adj
Control-Amido 0.5N     27.885714  10.455630  45.315798 0.0006224
Control-Amido 1N       26.885714   9.455630  44.315798 0.0009718
Control-Asulam 1N      21.314286   3.884202  38.744370 0.0107889
Metsulf 1N-Control    -29.314286 -46.744370 -11.884202 0.0003282
```

Table 24. ANOVA & Tukey test of 2019 mean number of living bracken shoots per m^2 in chemical treatment plots at Fawdon Farm, Northumberland

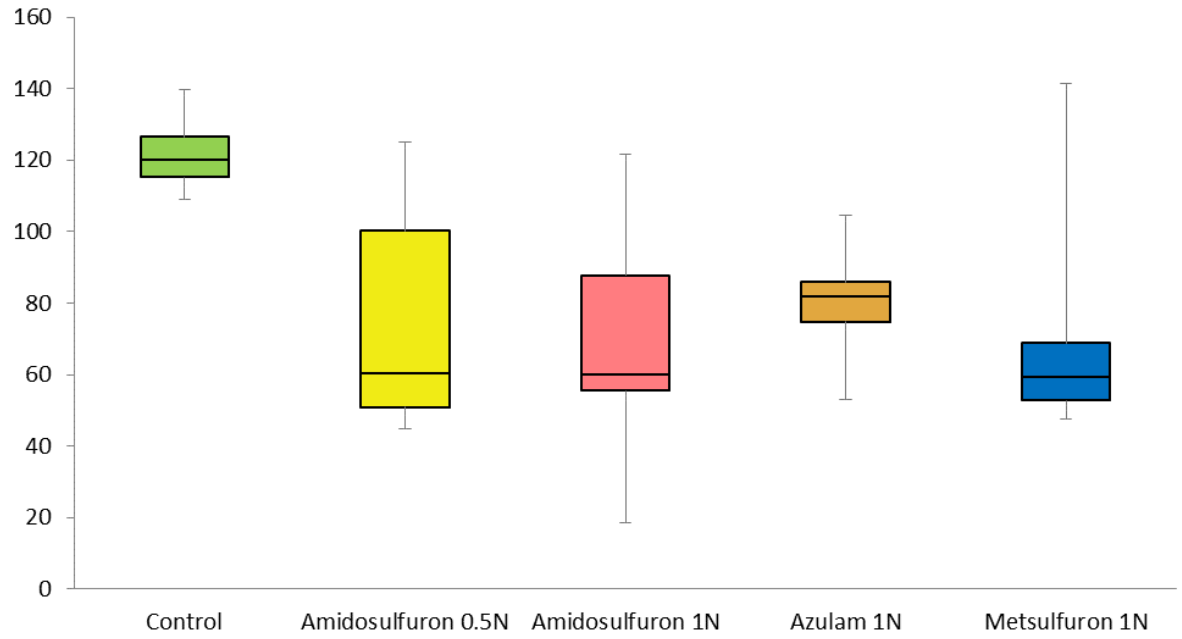


Figure 111. Median (min, Q1, Q3, max) of mean bracken frond height of tallest 10 fronds per plot in chemical treatment plots at Fawdon Farm, Northumberland, 2019

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	11406	2851.4	3.52	0.019	*
Residuals	28	22683	810.1			

Significant pairwise comparisons:

	diff	lwr	upr	p adj
Control-Amido 0.5N	50.771429	2.216094	99.326763	0.0370525
Control-Amido 1N	54.485714	5.930379	103.041049	0.0220244
Metsulf 1N-Control	-53.785714	-102.341049	-5.230379	0.0243313

Table 25. ANOVA & Tukey test of 2019 mean frond height in quadrats in chemical treatment plots at Fawdon Farm, Northumberland

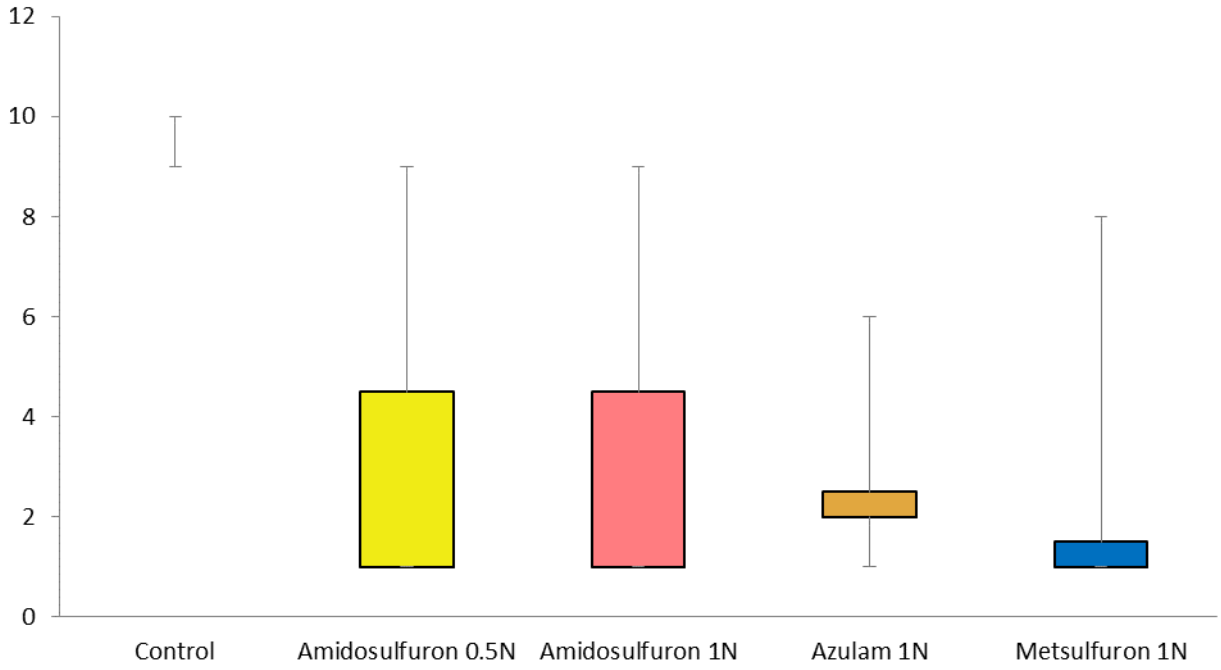


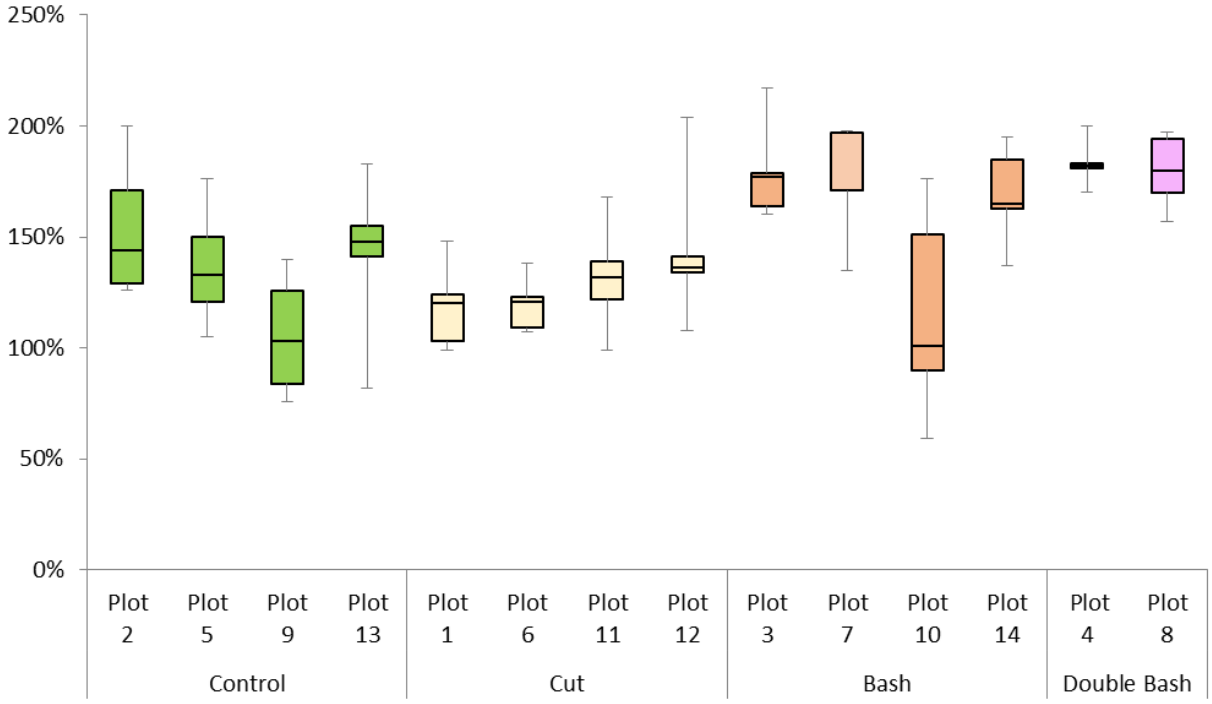
Figure 112. Median (min, Q1, Q3, max) bracken vigour score in chemical treatment plots at Fawdon Farm, Northumberland, 2019

Kruskal-Wallis chi-squared = 14.351, df = 4, p-value = 0.006254

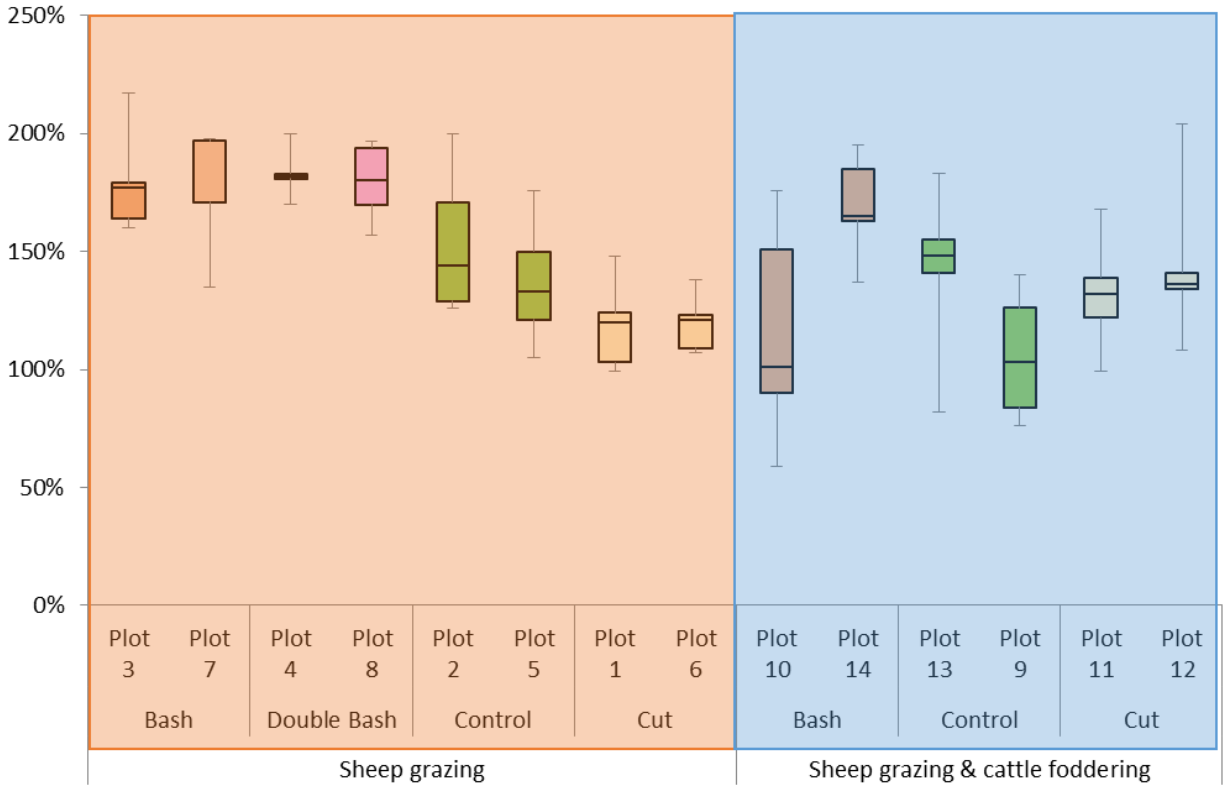
	Comparison	Z	P.unadj	P.adj
1	AmidosulfuronOpt5N - Amidosulfuron1N	0.0000000	1.000000000	1.000000000
2	AmidosulfuronOpt5N - Asulam1N	-0.9594815	0.337316259	0.481880370
3	Amidosulfuron1N - Asulam1N	-0.9594815	0.337316259	0.562193765
4	AmidosulfuronOpt5N - Control	-3.0831072	0.002048514	0.006828378
5	Amidosulfuron1N - Control	-3.0831072	0.002048514	0.010242568
6	Asulam1N - Control	-2.2072245	0.027298381	0.068245953
7	AmidosulfuronOpt5N - Metsulfuron1N	0.3099863	0.756571363	0.840634848
8	Amidosulfuron1N - Metsulfuron1N	0.3099863	0.756571363	0.945714204
9	Asulam1N - Metsulfuron1N	1.2694678	0.204274279	0.408548559
10	Control - Metsulfuron1N	3.3660847	0.000762433	0.007624330

Table 26. Kruskal Wallis test & Dunn's post-hoc test of 2019 bracken vigour scores between chemical treatments at Fawdon Farm, Northumberland

6.1.5 *VEGETATION DYNAMICS AT INGRAM FARM, NORTHUMBERLAND, FAWDON FARM, NORTHUMBERLAND & CHALLACOMBE FARM, DEVON*

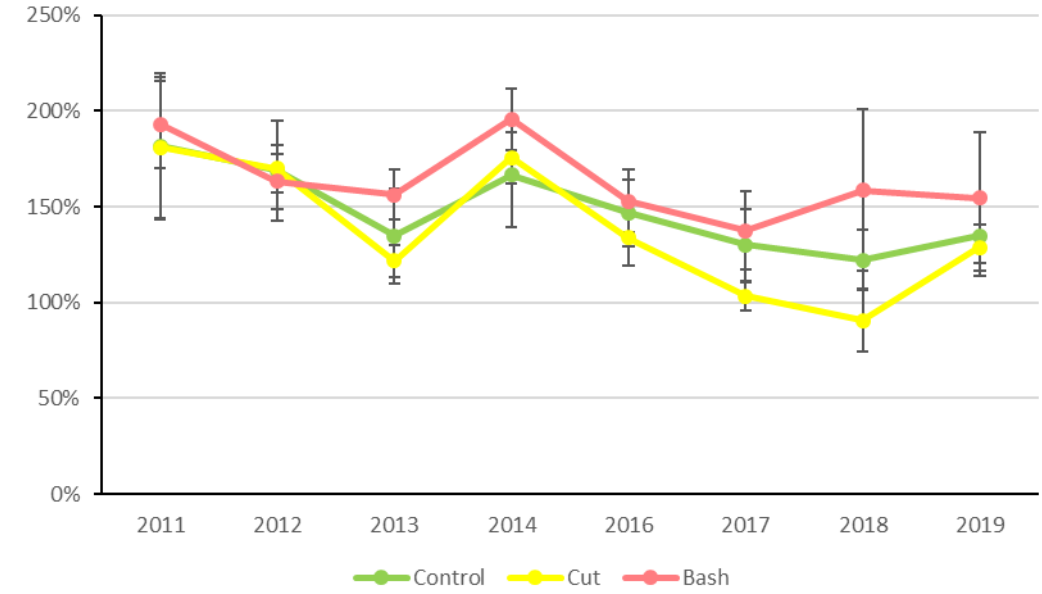


i

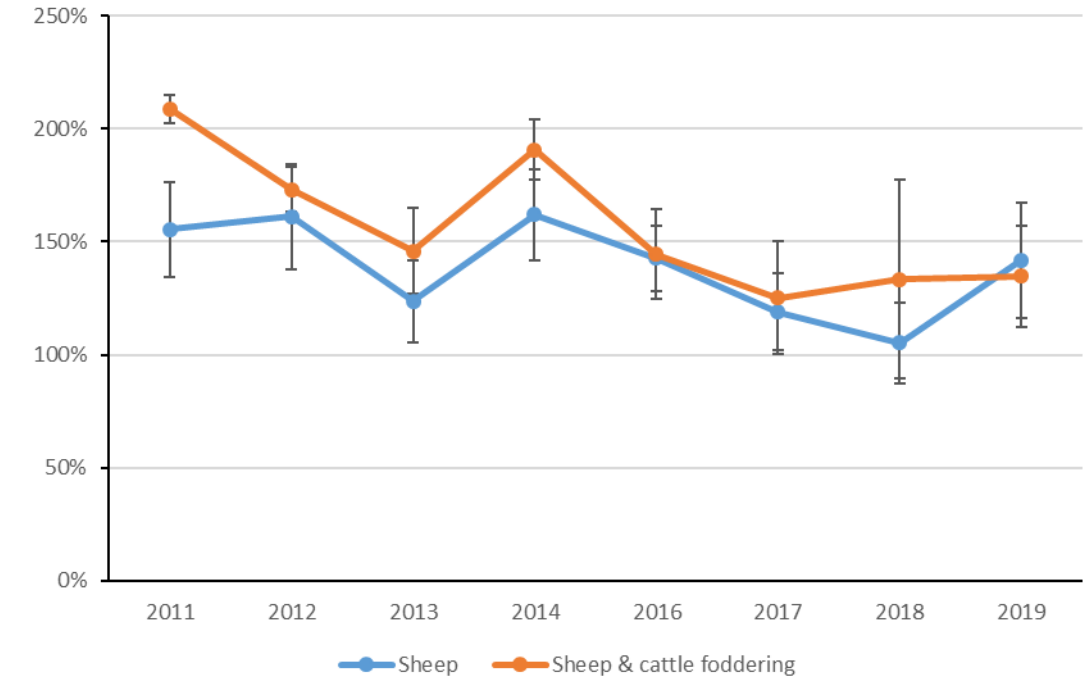


ii

Figure 113. Median (min, Q1, Q3, max) vegetation cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland



i

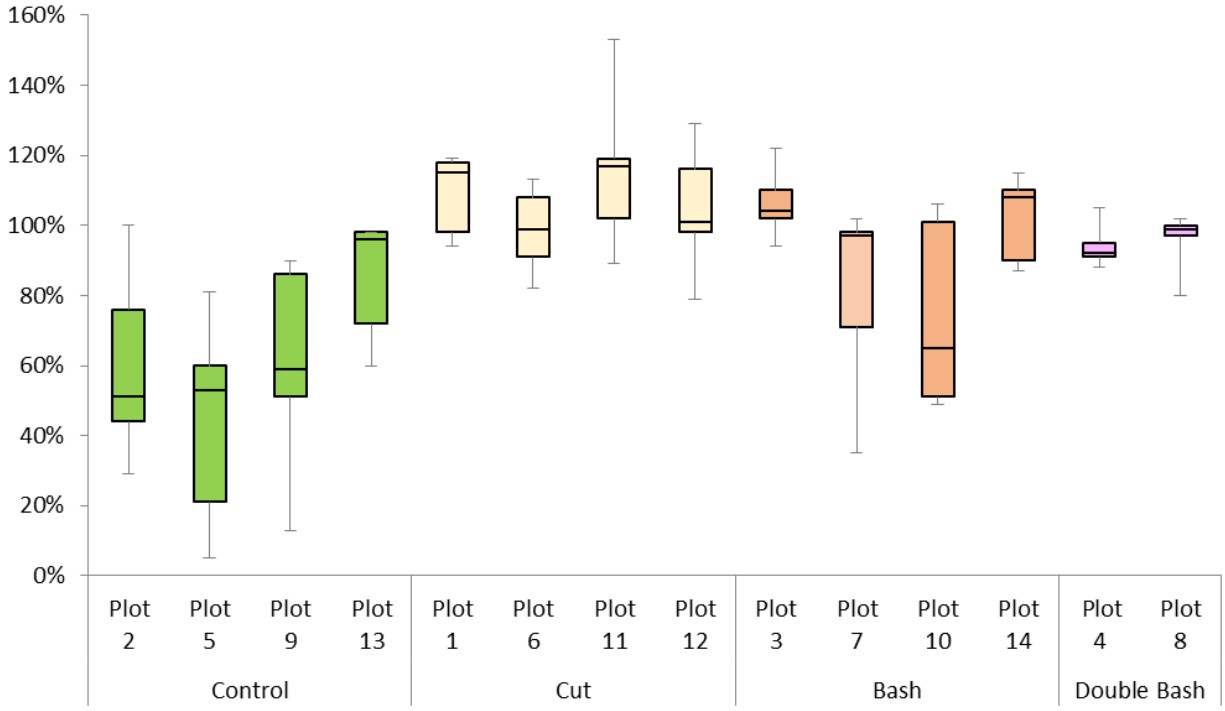


ii

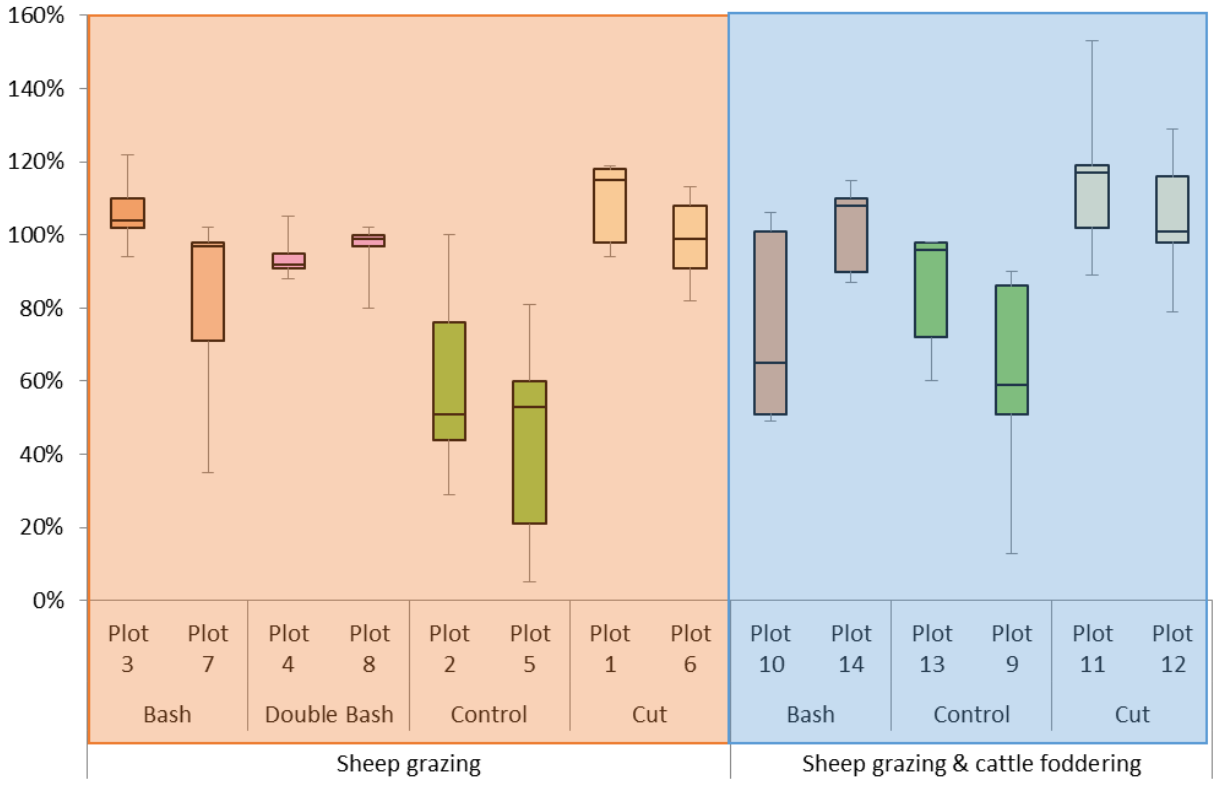
Figure 114. Mean (± standard deviation) vegetation cover (%) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Mechanical	2	0.000931	0.0004655	2.715	0.07733	.
Grazing	1	0.000300	0.0002998	1.749	0.19288	
Plot	7	0.003718	0.0005312	3.098	0.00961	**
Residuals	44	0.007545	0.0001715			

Table 27. ANOVA test on arcsine transformation of vegetation cover 2019 (%) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i

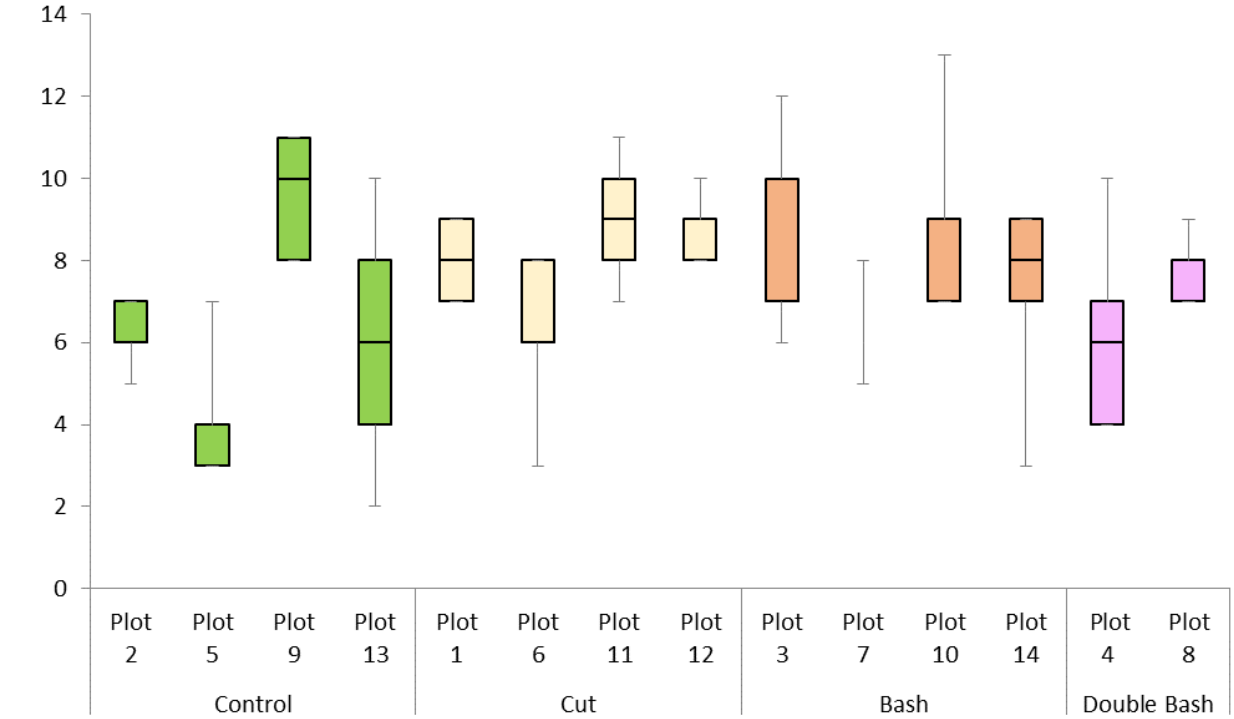


ii

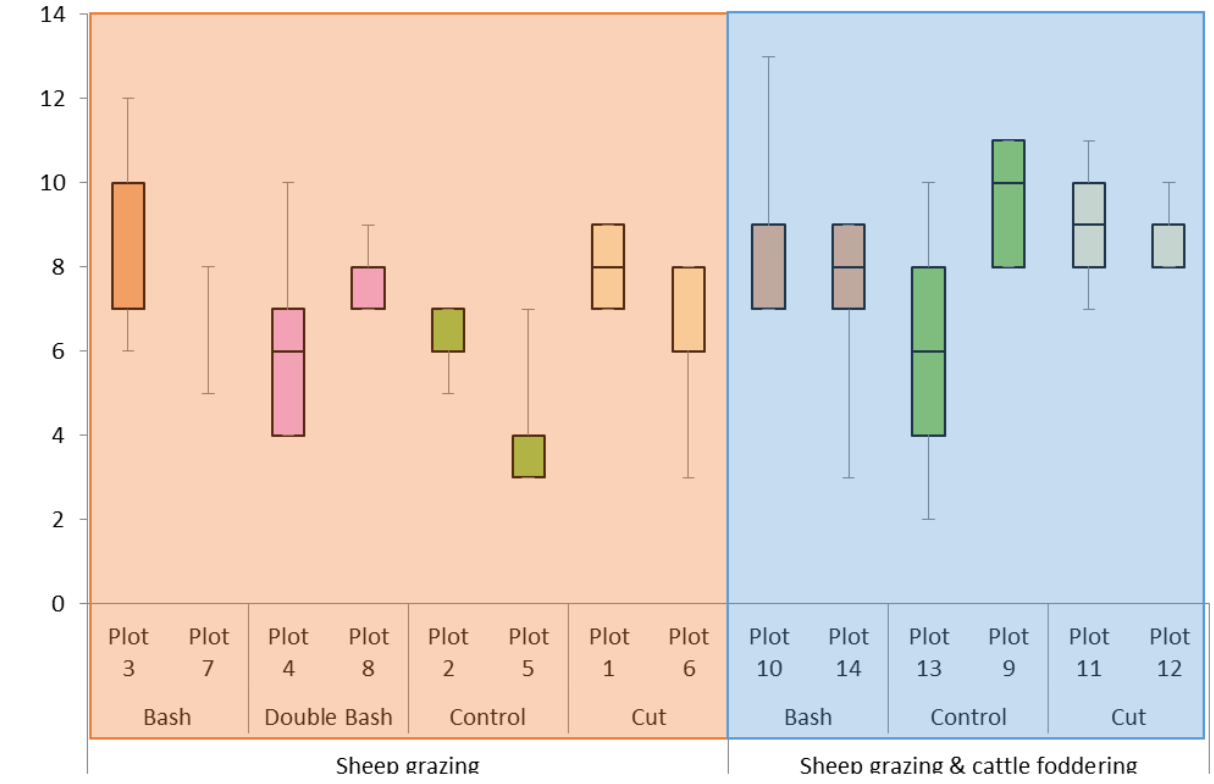
Figure 115. Median (min, Q1, Q3, max) understorey cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
            Df   Sum Sq  Mean Sq F value   Pr(>F)
Mechanical   2 0.007524 0.003762  15.771 6.85e-06 ***
Grazing      1 0.000777 0.000777   3.258   0.0779 .
Plot         7 0.002372 0.000339   1.420   0.2215
Residuals   44 0.010495 0.000239

Significant pairwise comparisons
Mechanical treatment
                          diff         lwr         upr     p adj
Cut-Control          0.02735419  0.01550822 0.039200151 0.0000038
Single Bash-Control  0.01561692  0.00282181 0.028412020 0.0134175
```

Table 28. ANOVA & Tukey range test on arcsine transformation of understorey cover 2019 (%) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i



ii

Figure 116. Median (min, Q1, Q3, max) species richness 2019 (# species present in quadrats), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  24.66   12.33   3.588 0.036004 *
Grazing      1  62.35   62.35  18.145 0.000106 ***
Plot         7  63.13    9.02   2.625 0.023476 *
Residuals   44 151.20    3.44

Significant pairwise comparisons:
Mechanical treatment
                      diff        lwr      upr     p adj
Cut-Control          1.5500000  0.1281702 2.971830 0.0298331

Grazing treatment
                     diff       lwr      upr     p adj
Sheep/Cattle-Sheep 2.114444 1.102738 3.126151 0.0001233
```

Table 29. ANOVA & Tukey range test on species richness 2019 (# species present in quadrats) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland

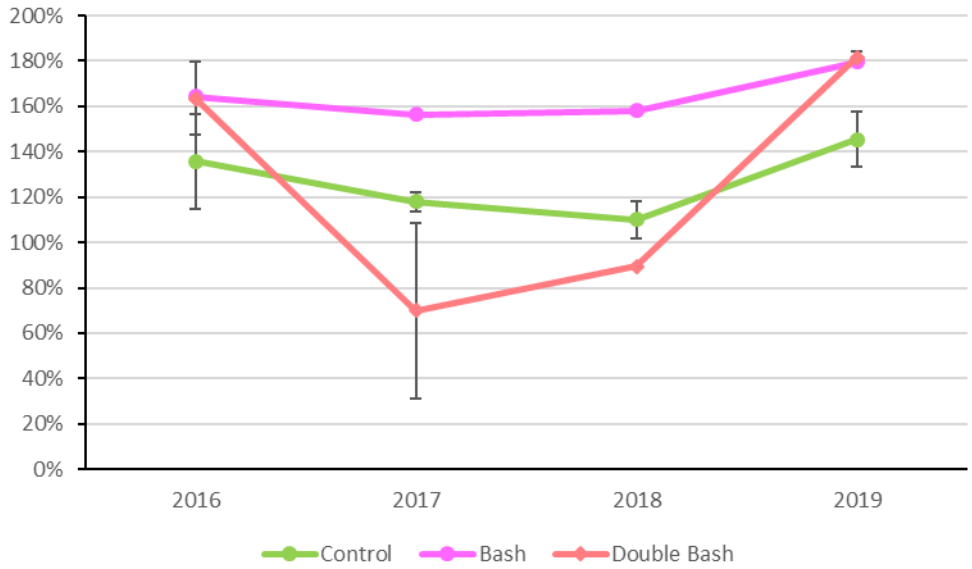


Figure 117. Mean (± standard deviation) vegetation cover (%) 2016-2019 in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

```
           Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical  2 0.7462  0.3731   7.100 0.00468 **
Plot        2 0.0755  0.0377   0.718 0.49973
Residuals  20 1.0509  0.0525
```

Significant pairwise comparisons:

```
                       diff        lwr       upr     p adj
Double Bash-Control   0.359  0.09964046 0.6183595 0.0060764
Single Bash-Control   0.339  0.02135073 0.6566493 0.0352103
```

Table 30. ANOVA & Tukey test of vegetation cover (%) in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
           Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical  2 1.3545  0.6772  17.292 4.36e-05 ***
Plot        2 0.0645  0.0322   0.823    0.453
Residuals  20 0.7833  0.0392

Significant pairwise comparisons
                       diff        lwr       upr     p adj
Double Bash-Control   0.429  0.2050830 0.6529170 0.0002765
Single Bash-Control   0.544  0.2697588 0.8182412 0.0001869
```

Table 31. ANOVA & Tukey range test on understorey cover (%) in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
           Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical  2   52.2   26.10   7.814 0.00311 **
Plot        2   17.0    8.50   2.545 0.10359
Residuals  20   66.8    3.34

Significant pairwise comparisons
                      diff        lwr      upr     p adj
Single Bash-Control    3.9  1.3674895 6.432511 0.0024704
```

Table 32. ANOVA & Tukey range test of species richness in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

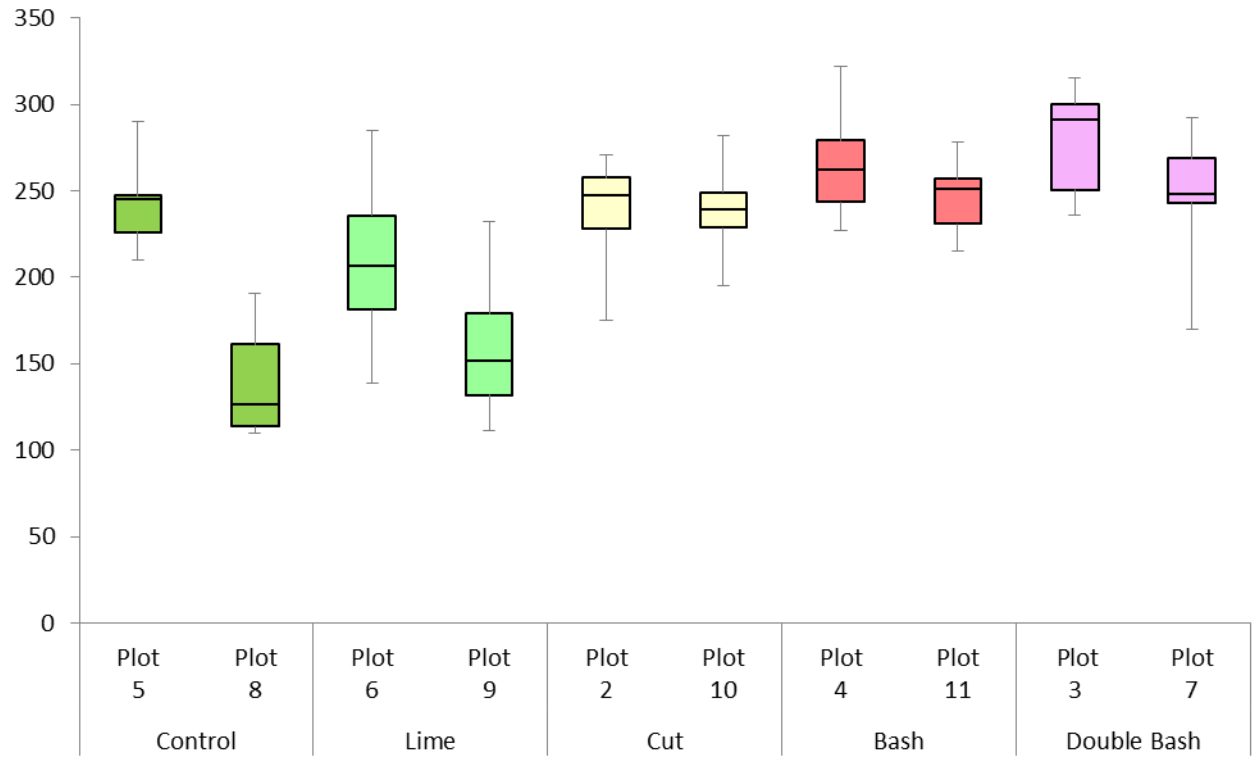


Figure 118. Median (min, Q1, Q3, max) vegetation cover 2019 (%) at Challacombe Farm, Devon, arranged according to mechanical & liming treatments

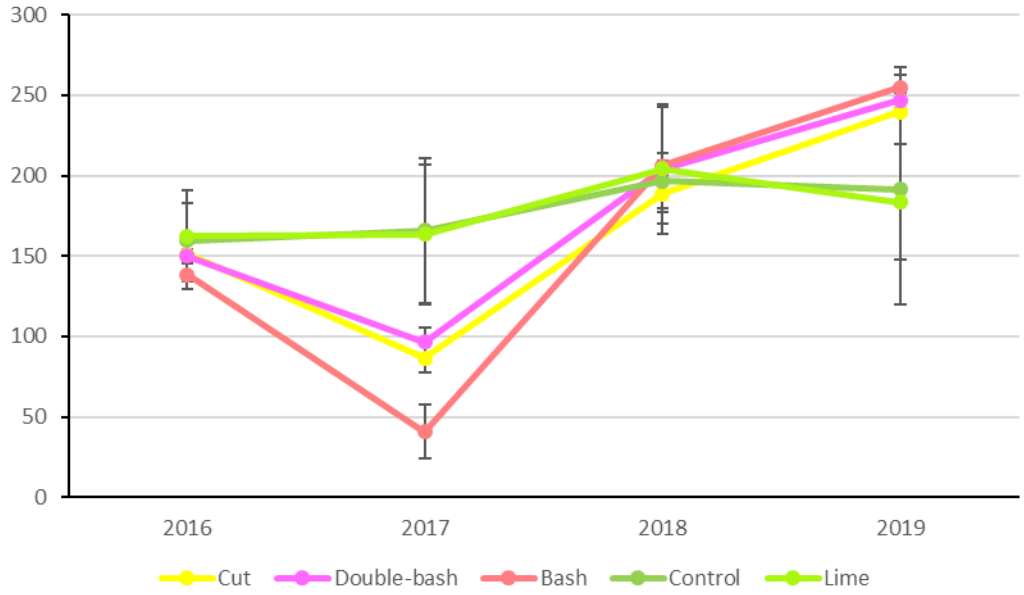


Figure 119. Mean (± standard deviation) vegetation cover (%) 2016-2019 at Challacombe Farm, Devon, split by mechanical & liming treatments

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4  11.00  2.7511   29.48 1.15e-15 ***
Plot         5   6.98  1.3960   14.96 1.14e-10 ***
Residuals   90   8.40  0.0933

Significant pairwise comparisons:

                       diff         lwr        upr     p adj
Control-Bash        -0.6355 -0.90444741 -0.3665526 0.0000000
Lime-Bash           -0.7125 -0.98144741 -0.4435526 0.0000000
Cut-Control          0.4830  0.21405259  0.7519474 0.0000274
Double-bash-Control  0.7325  0.46355259  1.0014474 0.0000000
Lime-Cut            -0.5600 -0.82894741 -0.2910526 0.0000010
Lime-Double-bash    -0.8095 -1.07844741 -0.5405526 0.0000000
```

Table 33. ANOVA & Tukey test of vegetation cover (%), 2019 at Challacombe Farm, Devon, according to plot & mechanical/liming treatment

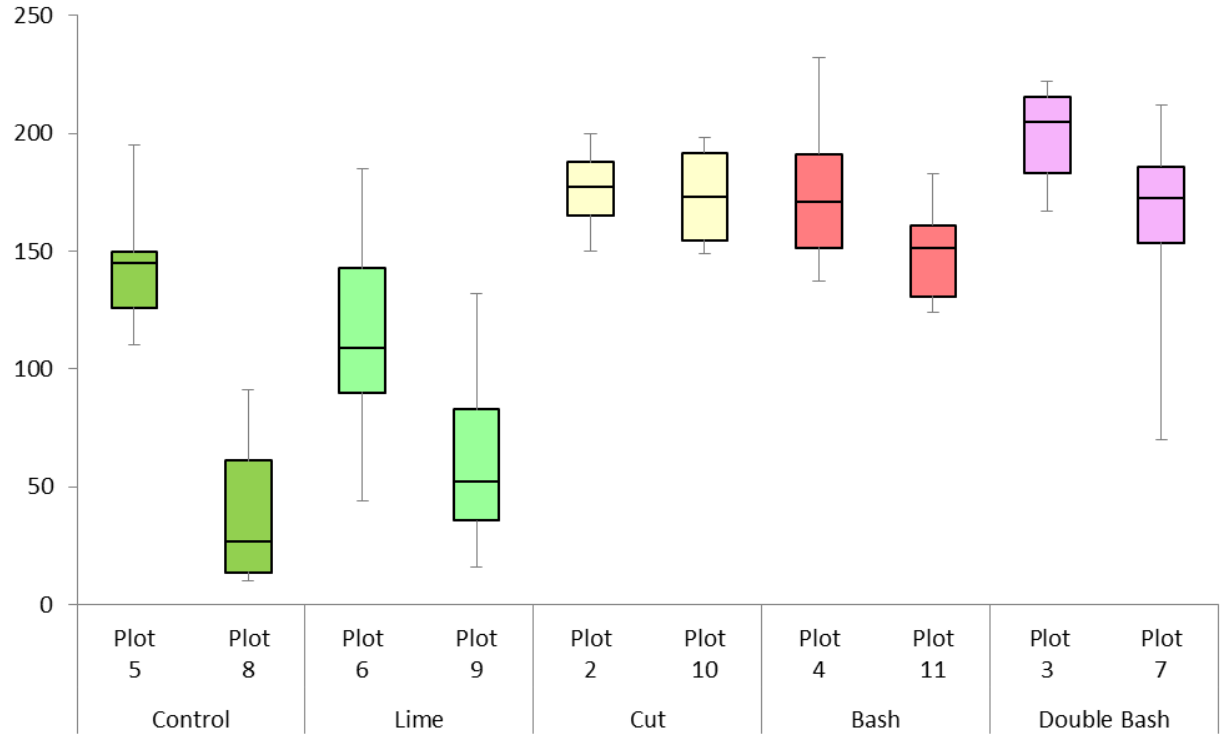


Figure 120. Median (min, Q1, Q3, max) understorey cover 2019 (%), at Challacombe Farm, Devon, arranged according to mechanical & liming treatments

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4 17.084   4.271   50.03  < 2e-16 ***
Plot         5  7.544   1.509   17.68 3.65e-12 ***
Residuals   90  7.683   0.085

Significant pairwise comparisons
Mechanical treatment
                       diff        lwr        upr     p adj
Control-Bash        -0.6915 -0.9487121 -0.4342879 0.0000000
Lime-Bash           -0.7460 -1.0032121 -0.4887879 0.0000000
Cut-Control          0.8255  0.5682879  1.0827121 0.0000000
Double-bash-Control  0.8975  0.6402879  1.1547121 0.0000000
Lime-Cut            -0.8800 -1.1372121 -0.6227879 0.0000000
Lime-Double-bash    -0.9520 -1.2092121 -0.6947879 0.0000000
```

Table 34. ANOVA & Tukey range test on understorey cover (%), 2019 at Challacombe Farm, Devon, according to plot & mechanical/liming treatment

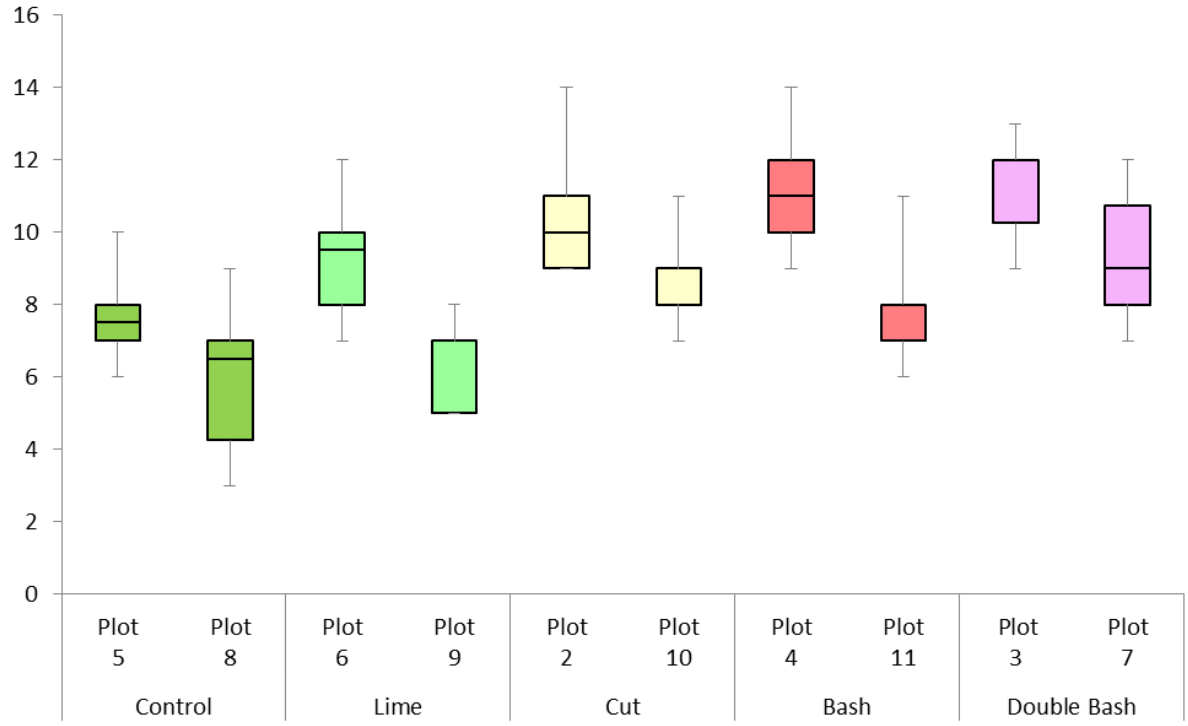


Figure 121. Median (min, Q1, Q3, max) species richness 2019 (# species present in quadrats), at Challacombe Farm, Devon, arranged according to mechanical & liming treatments

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4  171.1   42.78   19.23 1.83e-11 ***
Plot         5  151.9   30.38   13.66 6.47e-10 ***
Residuals   90  200.2    2.22

Significant pairwise comparisons:
                    diff        lwr        upr     p adj
Control-Bash       -2.70 -4.0129772 -1.3870228 0.0000013
Lime-Bash          -1.75 -3.0629772 -0.4370228 0.0032207
Cut-Control         2.75  1.4370228  4.0629772 0.0000008
Double-bash-Control 3.55  2.2370228  4.8629772 0.0000000
Lime-Cut           -1.80 -3.1129772 -0.4870228 0.0022580
Lime-Double-bash   -2.60 -3.9129772 -1.2870228 0.0000033
```

Table 35. ANOVA & Tukey range test on species richness 2019 (# species present in quadrats) in mechanical & liming treatment plots at Challacombe Farm, Devon

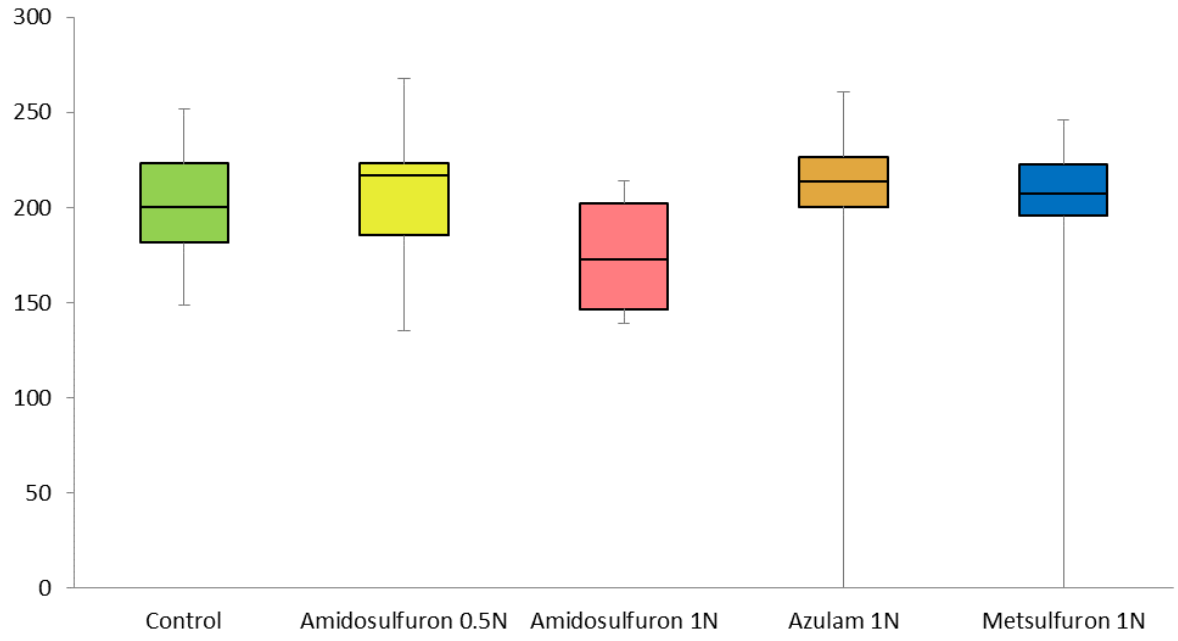


Figure 122. Median (min, Q1, Q3, max) vegetation cover 2019 (%), at Challacombe Farm, Devon, arranged according to chemical treatments

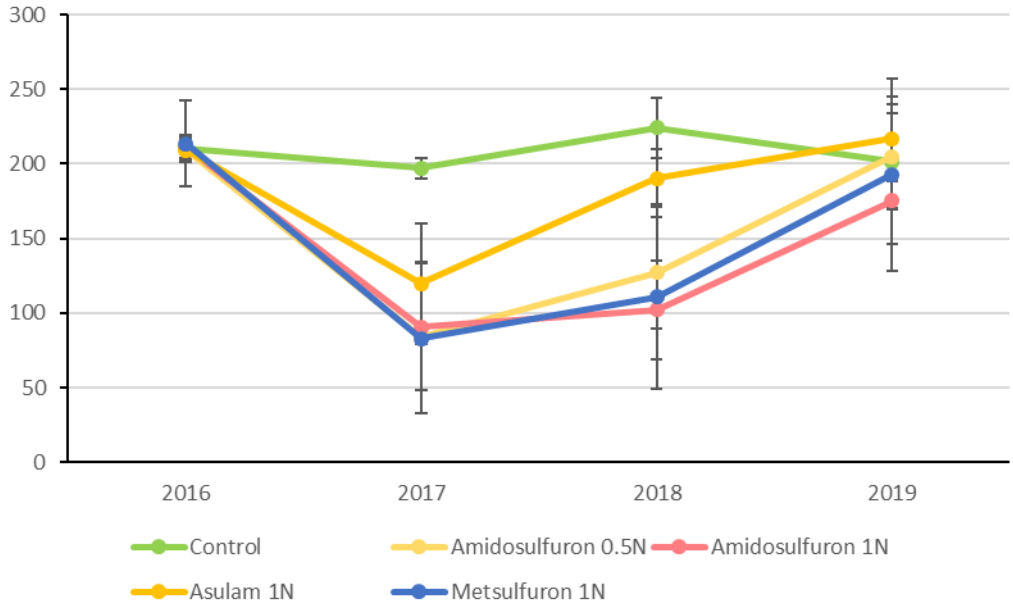


Figure 123. Mean (± standard deviation) vegetation cover (%) 2016-2019 at Challacombe Farm, Devon, split by chemical treatments

```
           Df Sum Sq Mean Sq F value Pr(>F)
Chemical    4  1.194 0.29841   3.347 0.0162 *
Residuals  53  4.726 0.08916
```

```
Significant pairwise comparisons:
                                  diff          lwr        upr    p adj
Asulam 1N-Amidosulfuron 1N  0.41734848  0.0653702977 0.76932667 0.0125194
```

Table 36. ANOVA & Tukey test on vegetation cover 2019 (%) in chemical treatment plots at Challacombe Farm, Devon

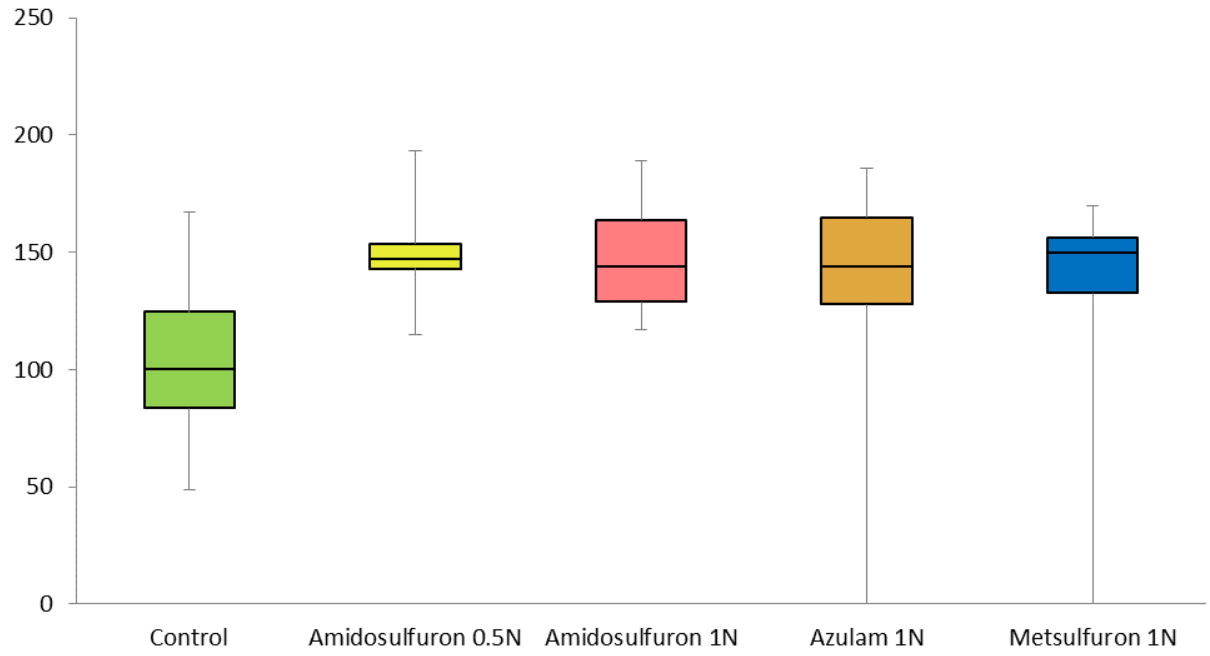


Figure 124. Median (min, Q1, Q3, max) understorey cover 2019 (%), at Challacombe Farm, Devon, arranged according to chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	1.785	0.4462	8.327	2.74e-05	***
Residuals	53	2.840	0.0536			

Significant pairwise comparisons:

	diff	lwr	upr	p adj
Control-Amidosulfuron 0.5N	-0.438333333	-0.7051966	-0.1714701	0.0002198
Control-Amidosulfuron 1N	-0.417500000	-0.6843632	-0.1506368	0.0004602
Control-Asulam 1N	-0.441287879	-0.7141488	-0.1684270	0.0002796
Metsulfuron 1N-Control	0.434015152	0.1611542	0.7068761	0.0003599

Table 37. ANOVA & Tukey range test on understorey cover 2019 at Challacombe Farm, Devon, according to chemical treatment

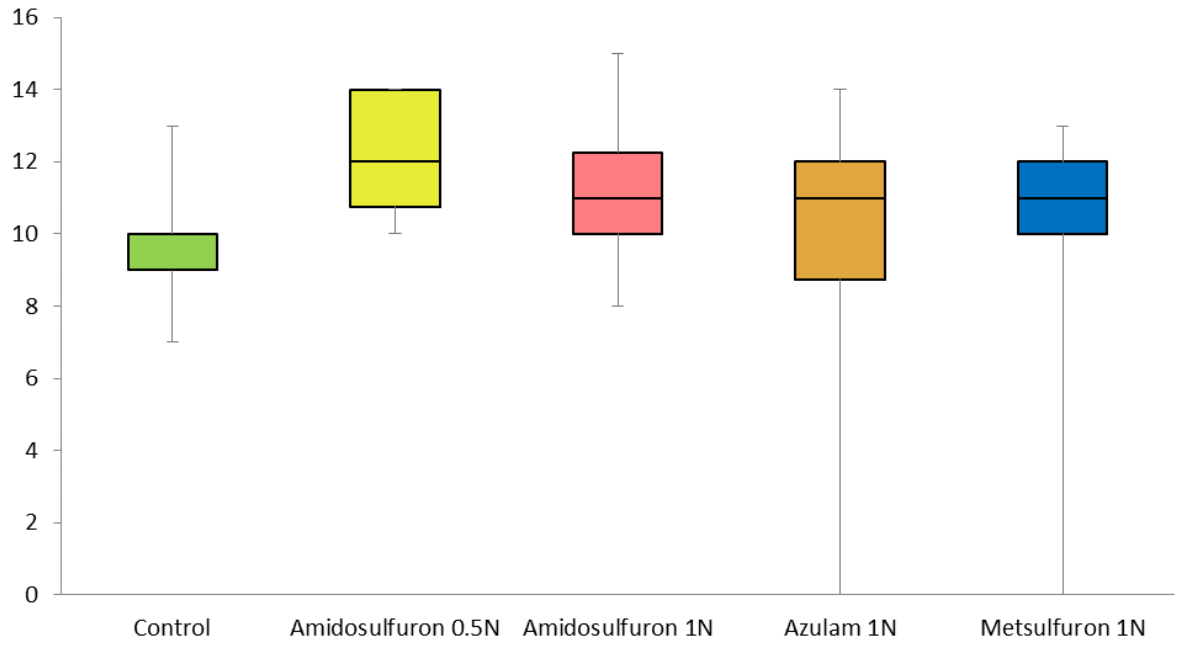


Figure 125. Median (min, Q1, Q3, max) species richness 2019 (# species present in quadrats), at Challacombe Farm, Devon, arranged according to chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	104.0	26.01	2.21	0.0936	.
Residuals	28	329.5	11.77			

Table 38. ANOVA test on species richness 2019 (# species present in quadrats) in chemical treatment plots at Challacombe Farm, Devon

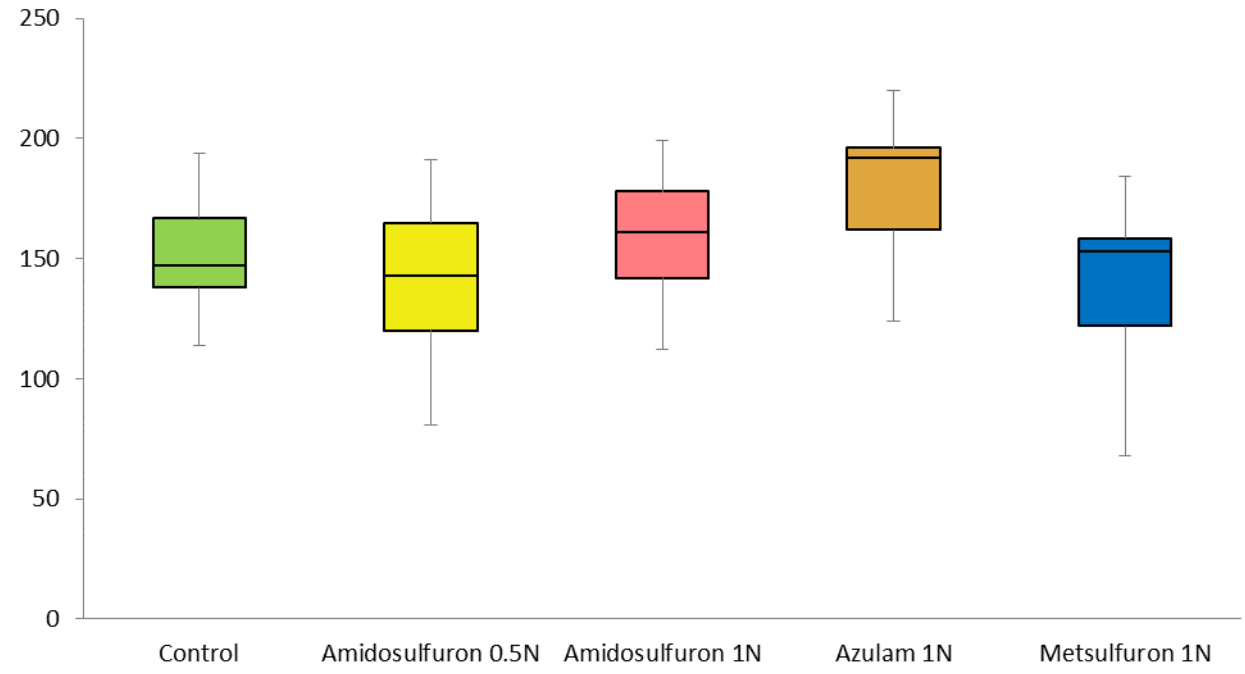


Figure 126. Median (min, Q1, Q3, max) vegetation cover 2019 (%), at Fawdon Farm, Northumberland, arranged according to chemical treatments

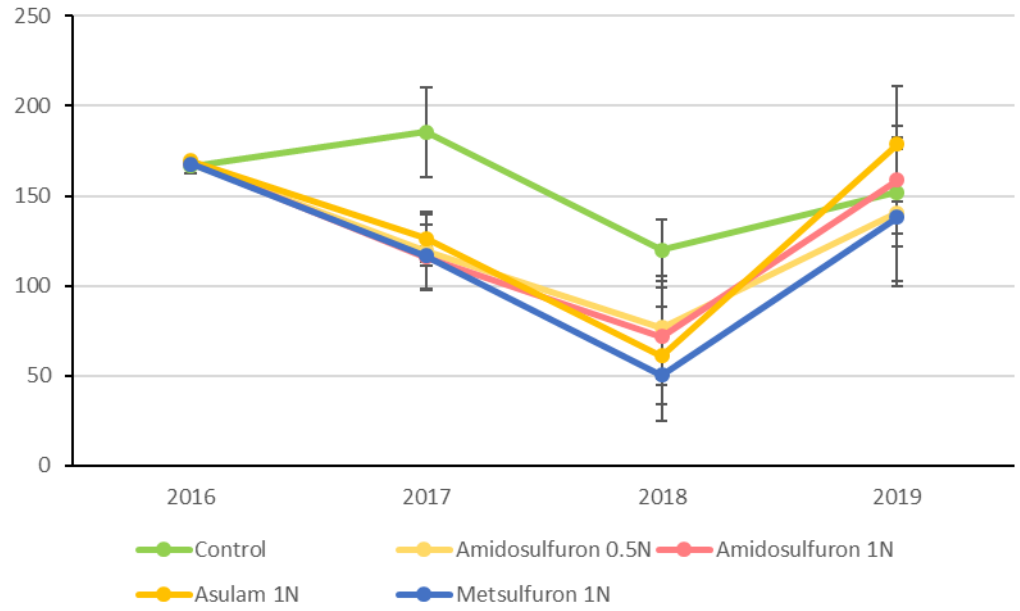


Figure 127. Mean (± standard deviation) vegetation cover (%) 2016-2019 at Fawdon Farm, Northumberland, split by chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Chemical	4	0.737	0.1842	1.564	0.211
Residuals	28	3.297	0.1178		

Table 39. ANOVA test on vegetation cover 2019 (%) in chemical treatment plots at Fawdon Farm, Northumberland

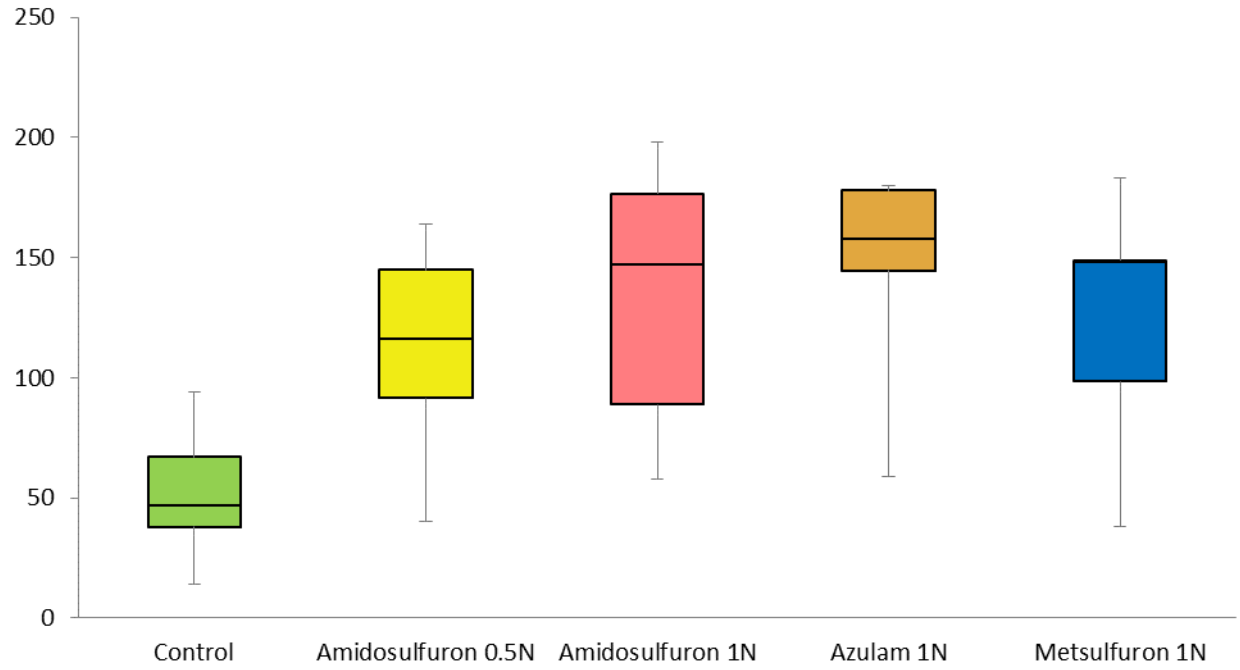


Figure 128. Median (min, Q1, Q3, max) understorey cover 2019 (%), at Fawdon Farm, Northumberland, arranged according to chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	2.456	0.6140	2.605	0.0572	.
Residuals	28	6.600	0.2357			

Table 40. ANOVA test on understorey cover 2019 at Fawdon Farm, Northumberland, according to chemical treatment

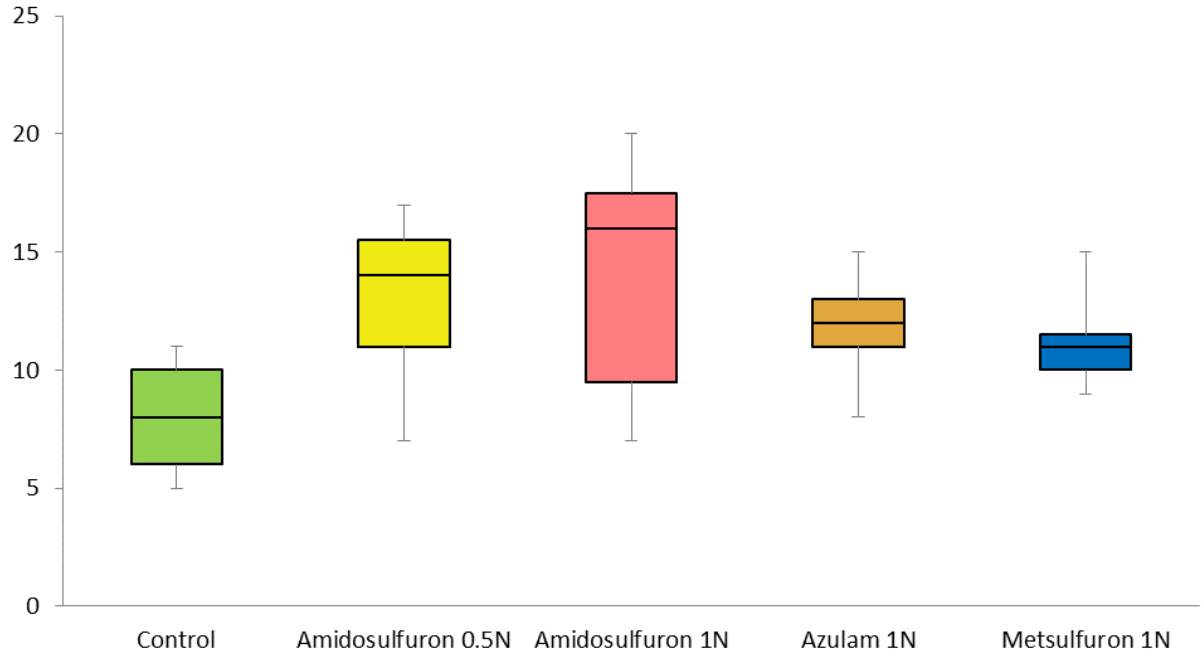


Figure 129. Median (min, Q1, Q3, max) species richness 2019 (# species present in quadrats), at Fawdon Farm, Northumberland, arranged according to chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	104.0	26.01	2.21	0.0936	.
Residuals	28	329.5	11.77			

Table 41. ANOVA test on species richness 2019 (# species present in quadrats) in chemical treatment plots at Fawdon Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2    777     388   1.575    0.217
Grazing      1  11310   11310  45.863 1.25e-08 ***
Residuals   51  12577     247
```

Table 42. ANOVA test of 2011 NVC U4b (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2    654     327   1.142    0.327
Grazing      1  13515   13515  47.160 8.82e-09 ***
Residuals   51  14615     287
```

Table 43. ANOVA test of 2011 NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2     33      16   0.123    0.884
Grazing      1   3870    3870  29.138 1.77e-06 ***
Residuals   51   6774     133
```

Table 44. ANOVA test of 2011 NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   2     27   13.75   0.184  0.832
Grazing      1     12   12.03   0.161  0.689
Residuals   51   3800   74.51
```

Table 45. ANOVA test of 2011 NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2   6002    3001   8.512 0.000646 ***
Grazing      1  12120   12120  34.381 3.35e-07 ***
Residuals   51  17979     353

Significant pairwise comparisons
Mechanical treatment

                     diff        lwr        upr     p adj
Cut-Control         16.60   2.267273  30.932727 0.0195929
Single Bash-Cut    -25.55 -41.031115 -10.068885 0.0006232

Grazing treatment
                  diff      lwr      upr p adj
SheepCattle-Sheep 29.48 19.27249 39.68751 4e-07
```

Table 46. ANOVA & Tukey test of 2019 NVC U4b (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland; *Holcus lanatus-Trifolium repens* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   2   2058    1029   2.680 0.07819 .
Grazing      1   3685    3685   9.602 0.00316 **
Residuals   51  19574     384
```

Table 47. ANOVA test of 2019 NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  11895    5948   9.736 0.000262 ***
Grazing      1    583     583   0.954 0.333218
Residuals   51  31154     611

Significant pairwise comparisons
Mechanical treatment
                      diff       lwr       upr     p adj
Cut-Control         -26.450000 -45.31720 -7.582804 0.0038802
Single Bash-Cut      34.416667  14.03777 54.795567 0.0004635
```

Table 48. ANOVA & Tukey test of 2019 NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  23877   11939  20.196 3.47e-07 ***
Grazing      1    635     635   1.074    0.305
Residuals   51  30148     591

Significant pairwise comparisons
Mechanical treatment
                     diff       lwr       upr     p adj
Cut-Control         -44.1 -62.66005 -25.53995 0.0000016
Single Bash-Cut      42.2  22.15285  62.24715 0.0000159
```

Table 49. ANOVA & Tukey test of 2019 NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) scores, Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4  769.3  192.33   7.368 3.27e-05 ***
Residuals   95 2480.1   26.11

Significant pairwise comparisons
                     diff        lwr        upr     p adj
Cut-Bash            -5.75 -10.243122 -1.2568775 0.0051727
Cut-Control         -7.85 -12.343122 -3.3568775 0.0000452
Double-bash-Control -5.65 -10.143122 -1.1568775 0.0063080
Lime-Control        -5.20  -9.693122 -0.7068775 0.0148524
```

Table 50. ANOVA & Tukey test of 2016 NVC U20 (*Pteridium aquilinum - Galium saxatile* community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   4   3623   905.7   3.353  0.013 *
Residuals   95  25659   270.1

Significant pairwise comparisons
                      diff         lwr       upr     p adj
Cut-Control         -17.75 -32.2024155 -3.297584 0.0081557
Double-bash-Cut      14.65   0.1975845 29.102416 0.0453029
```

Table 51. ANOVA & Tukey test of 2016 NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   2239   559.9   10.09 7.55e-07 ***
Residuals   95   5272    55.5

Significant pairwise comparisons
                    diff        lwr         upr     p adj
Cut-Bash           -11.80 -18.351189 -5.24881062 0.0000246
Double-bash-Bash   -12.00 -18.551189 -5.44881062 0.0000174
Cut-Control         -8.70 -15.251189 -2.14881062 0.0033315
Double-bash-Control -8.90 -15.451189 -2.34881062 0.0025056
```

Table 52. ANOVA & Tukey test of 2016 NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   3025   756.4   9.782 1.14e-06 ***
Residuals   95   7345    77.3

Significant pairwise comparisons
                    diff         lwr        upr     p adj
Cut-Bash           -12.95 -20.6826302 -5.2173698 0.0001003
Double-bash-Bash   -15.10 -22.8326302 -7.3673698 0.0000042
Cut-Control         -7.90 -15.6326302 -0.1673698 0.0427433
Double-bash-Control -10.05 -17.7826302 -2.3173698 0.0043193
Lime-Double-bash     9.05   1.3173698 16.7826302 0.0133319
```

Table 53. ANOVA & Tukey test of 2016 NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   4  48877   12219   32.09 <2e-16 ***
Residuals   95  36169     381

Significant pairwise comparisons
                    diff        lwr        upr     p adj
Double-bash-Bash   -20.35 -37.508728  -3.191272 0.0116976
Lime-Bash          -50.10 -67.258728 -32.941272 0.0000000
Double-bash-Control -23.35 -40.508728  -6.191272 0.0024521
Lime-Control       -53.10 -70.258728 -35.941272 0.0000000
Double-bash-Cut    -31.95 -49.108728 -14.791272 0.0000123
Lime-Cut           -61.70 -78.858728 -44.541272 0.0000000
Lime-Double-bash   -29.75 -46.908728 -12.591272 0.0000524
```

Table 54. ANOVA & Tukey test of 2019 NVC U4 (*Festuca ovina - Agrostis capillaris - Galium saxatile* grassland) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   3325   831.3   9.585 1.49e-06 ***
Residuals   95   8239    86.7

Significant pairwise comparisons
                    diff        lwr         upr     p adj
Cut-Bash            9.05   0.8605644 17.23943559 0.0226427
Double-bash-Bash   13.95   5.7605644 22.13943559 0.0000733
Lime-Cut           -10.70 -18.8894356 -2.51056441 0.0040571
Lime-Double-bash   -15.60 -23.7894356 -7.41056441 0.0000074
```

Table 55. ANOVA & Tukey test of 2019 NVC U20 (*Pteridium aquilinum - Galium saxatile* community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   6757  1689.2   13.98 5.26e-09 ***
Residuals   95  11478   120.8

Significant pairwise comparisons
                    diff         lwr        upr     p adj
Double-bash-Bash   11.35   1.6837557  21.016244 0.0129137
Lime-Bash         -11.10 -20.7662443  -1.433756 0.0159915
Cut-Control        12.60   2.9337557  22.266244 0.0041718
Double-bash-Control 15.25   5.5837557  24.916244 0.0002826
Lime-Cut          -19.80 -29.4662443 -10.133756 0.0000013
Lime-Double-bash  -22.45 -32.1162443 -12.783756 0.0000000
```

Table 56. ANOVA & Tukey test of 2019 NVC U20a (*Pteridium aquilinum – Galium saxatile*; *Anthoxanthum odoratum* sub-community) scores, Challacombe Farm, Devon

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   4   1087  271.76   3.061 0.0203 *
Residuals   95   8435   88.79

Significant pairwise comparisons
                   diff        lwr       upr     p adj
Cut-Control      -10.05 -18.336127 -1.763873 0.0093070
```

Table 57. ANOVA & Tukey test of 2019 NVC U20b (*Pteridium aquilinum – Galium saxatile*; *Vaccinium myrtillus – Dicranum scoparium* sub-community) scores, Challacombe Farm, Devon

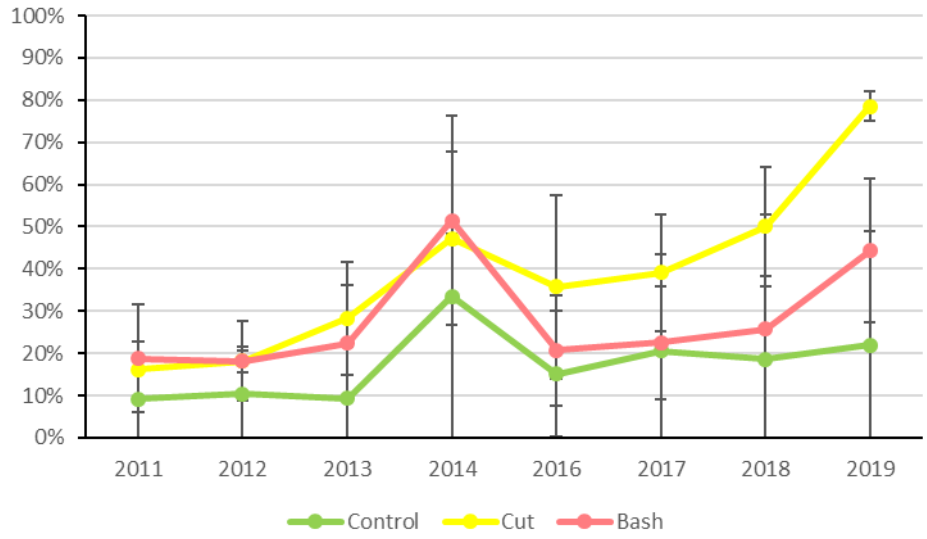
```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   4   9280  2320.1   16.67 2.21e-10 ***
Residuals   95  13222   139.2

Significant pairwise comparisons
                    diff        lwr        upr     p adj
Control-Bash       16.85   6.475494  27.224506 0.0001728
Lime-Bash          13.65   3.275494  24.024506 0.0037306
Cut-Control       -25.65 -36.024506 -15.275494 0.0000000
Double-bash-Control -17.95 -28.324506  -7.575494 0.0000545
Lime-Cut           22.45  12.075494  32.824506 0.0000003
Lime-Double-bash   14.75   4.375494  25.124506 0.0013674
```

Table 58. ANOVA & Tukey test of 2019 NVC U20c (*Pteridium aquilinum – Galium saxatile*; species-poor sub-community) scores, Challacombe Farm, Devon

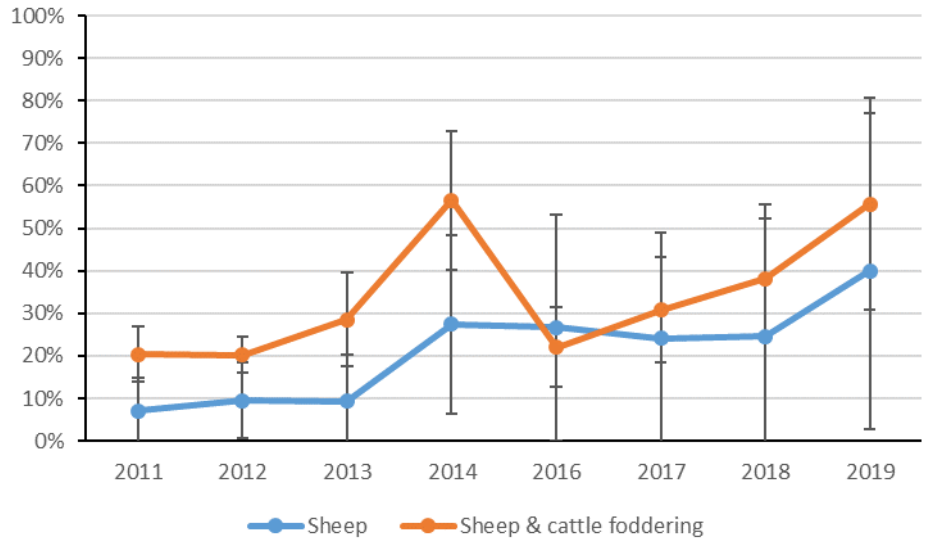
6.2 SELECTED SPECIES COVER DATA FROM QUADRATS AT INGRAM FARM, FAWDON FARM, NORTHUMBERLAND & CHALLACOMBE FARM DEVON

6.2.1 *PERCENTAGE COVER OF SELECTED SPECIES ON INGRAM FARM, 2011-2014 & 2016-2019*

Figures 130-140 (below) show the recorded mean cover of selected species according to treatment from 2011-2014 and in 2016-2019. The 2011-14 data are from the report which documents the previous iteration of this project (Scott *et al* 2014). In 2013 the vegetation data were recorded two weeks earlier than normal, which appears to have resulted in some dramatic changes in recorded cover that year when compared with adjacent years' data.

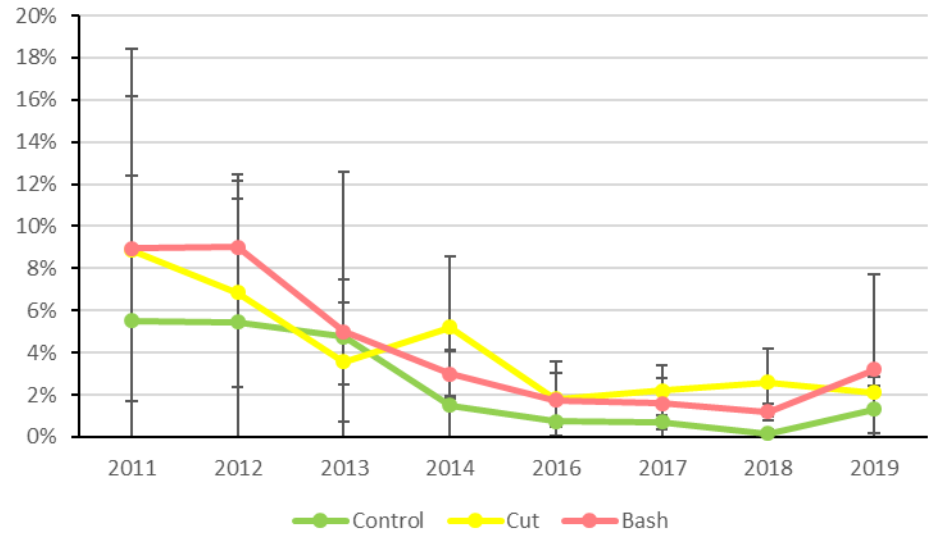


i

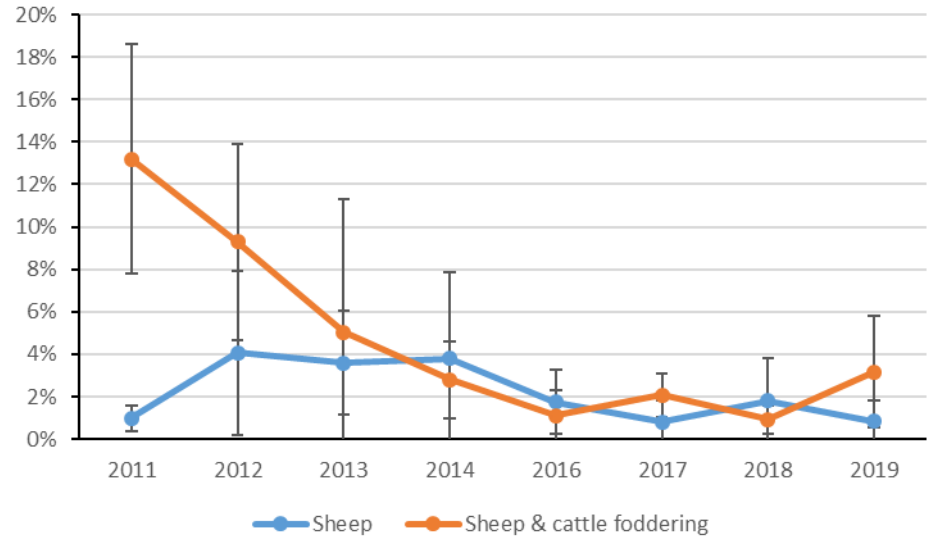


ii

Figure 130. *Agrostis capillaris* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

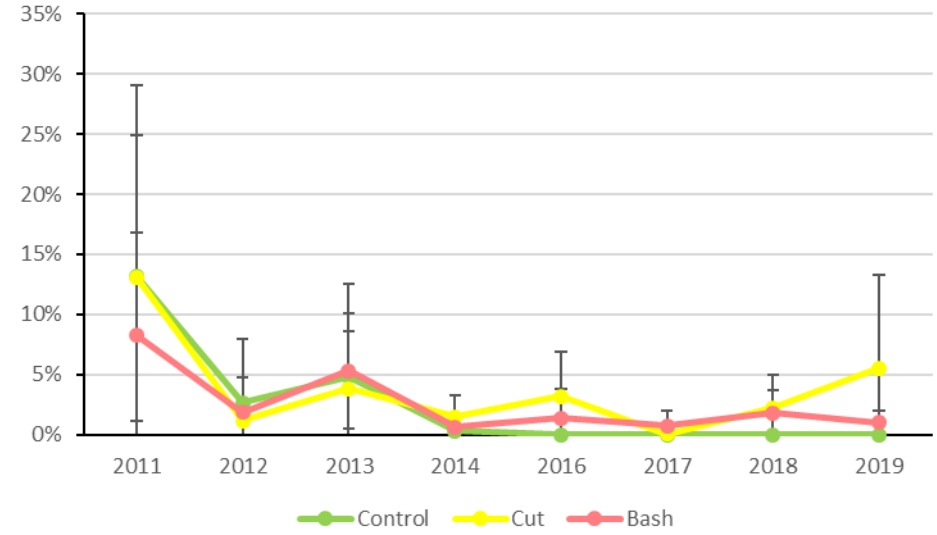


i

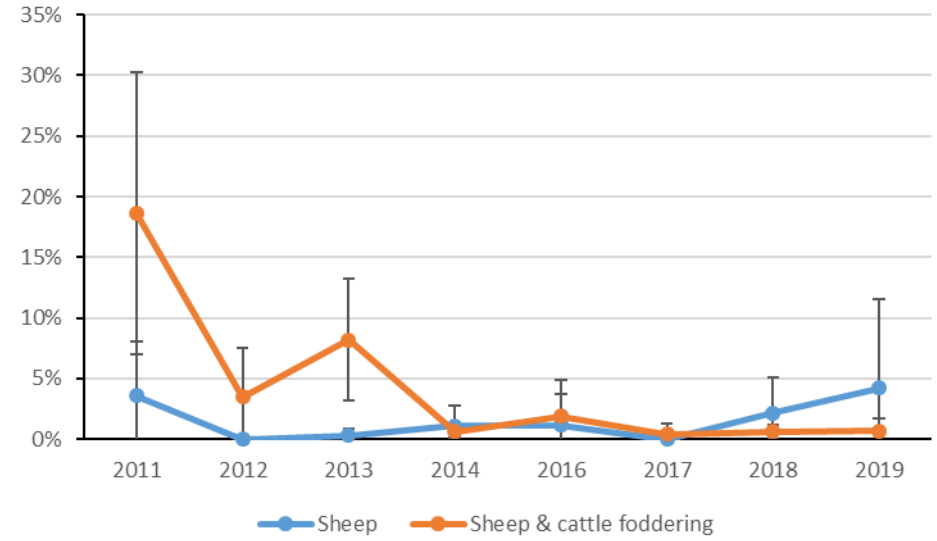


ii

Figure 131. *Anthoxanthum odoratum* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

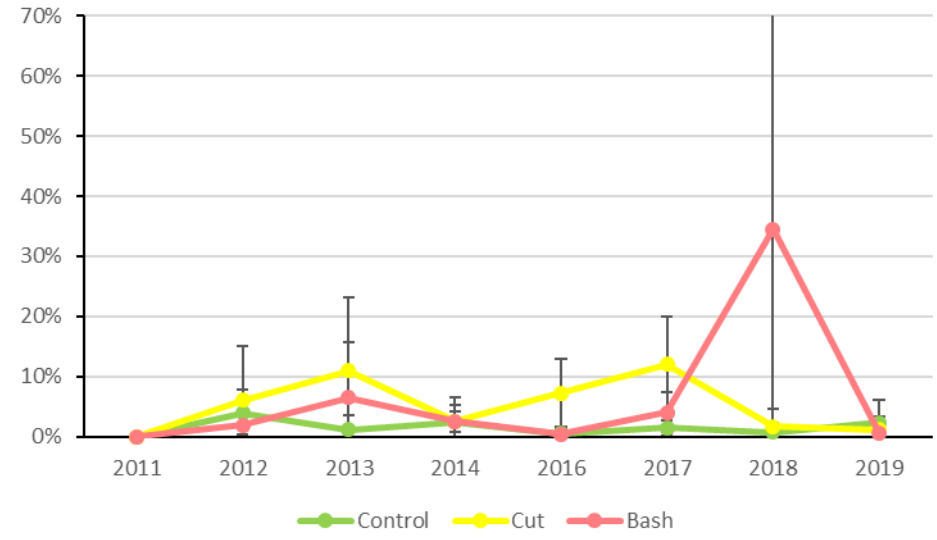


i

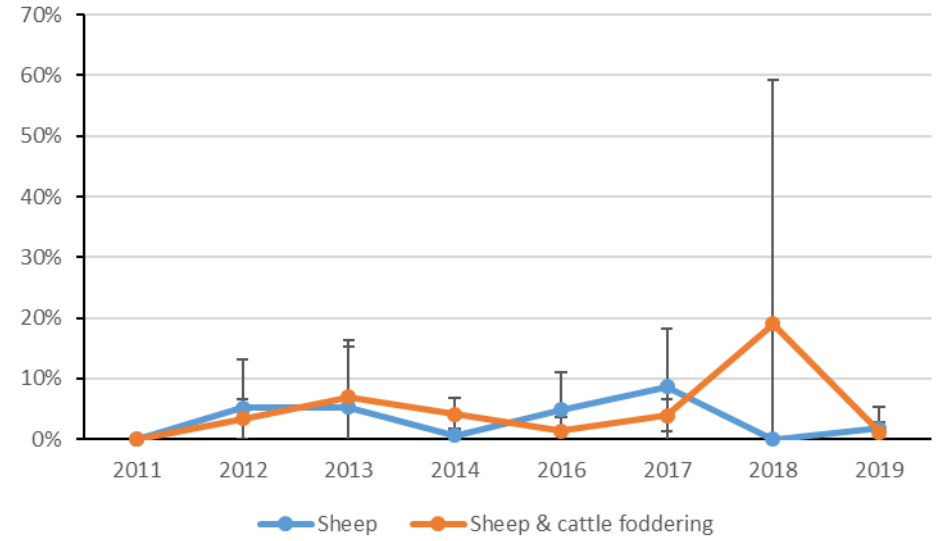


ii

Figure 132. *Festuca ovina* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

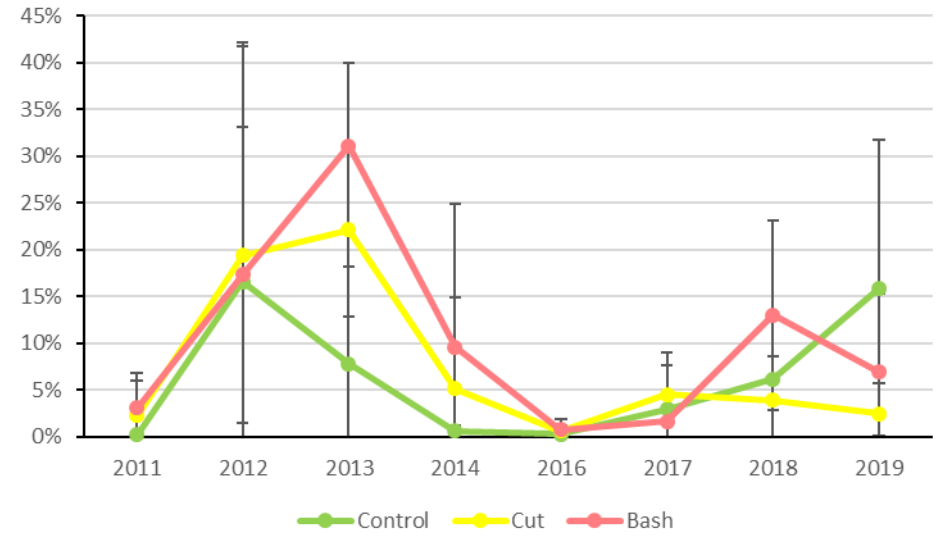


i

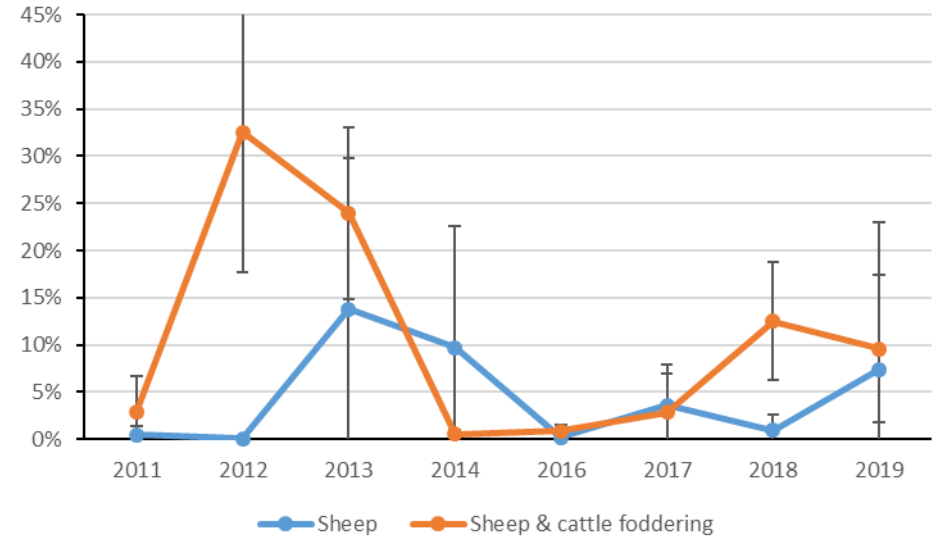


ii

Figure 133. *Festuca rubra* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

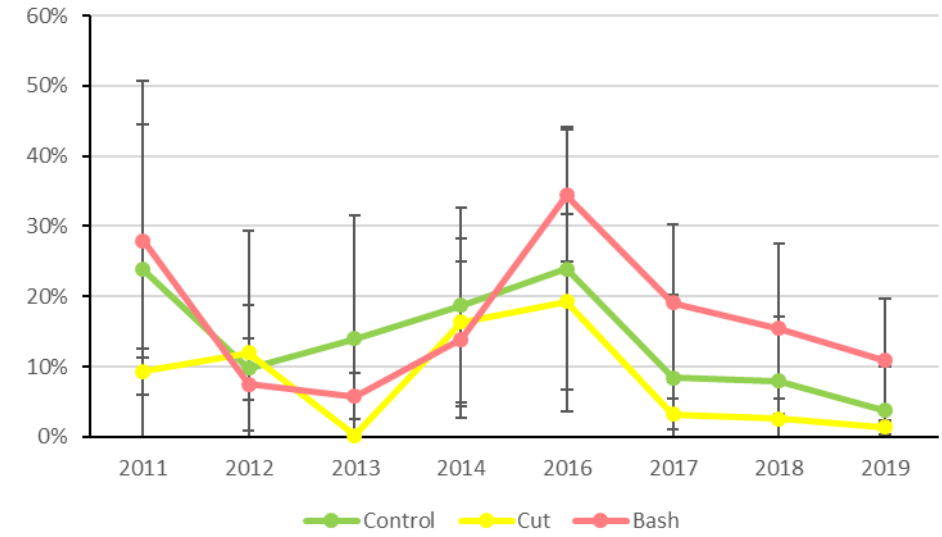


i

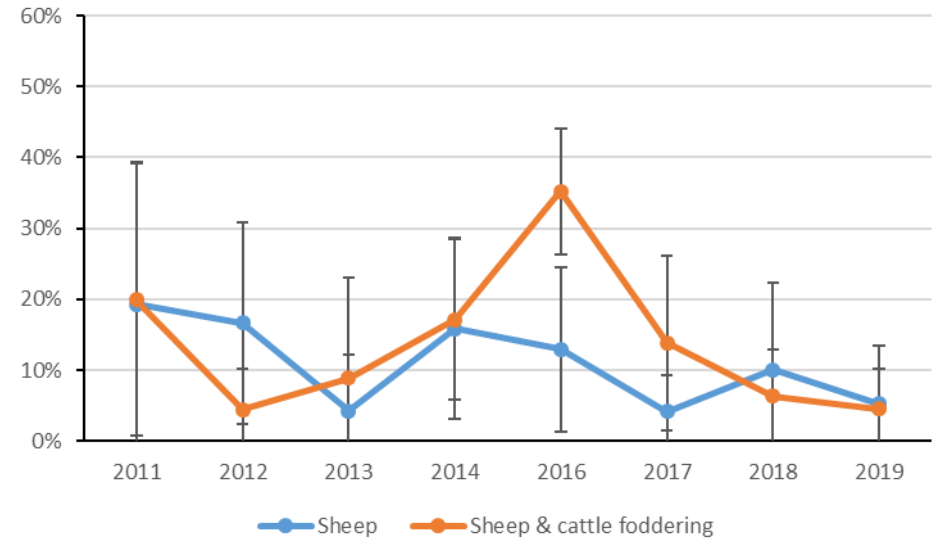


ii

Figure 134. *Holcus lanatus* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

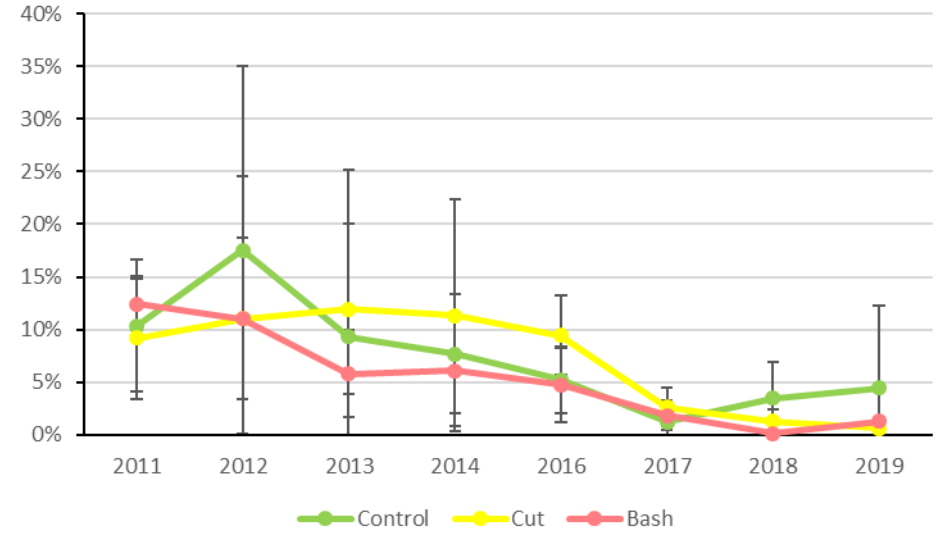


i

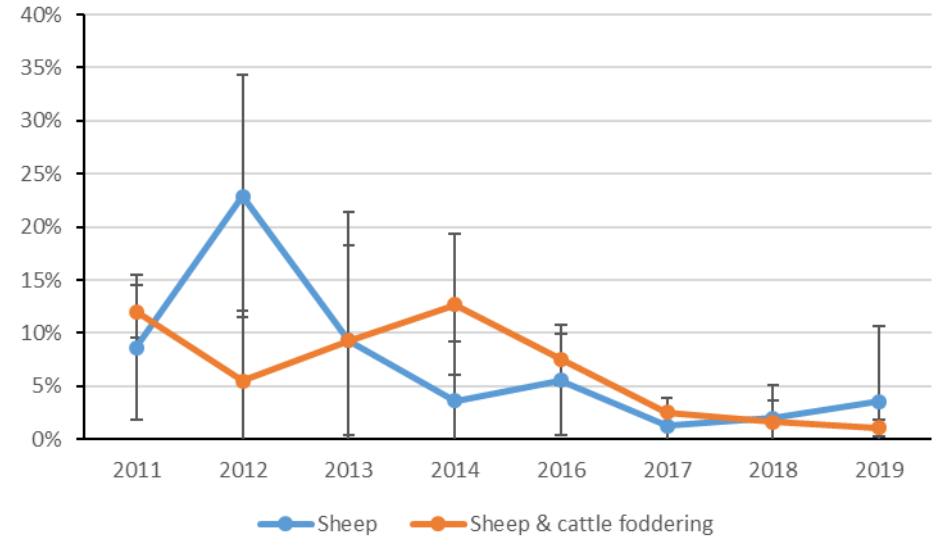


ii

Figure 135. *Holcus mollis* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

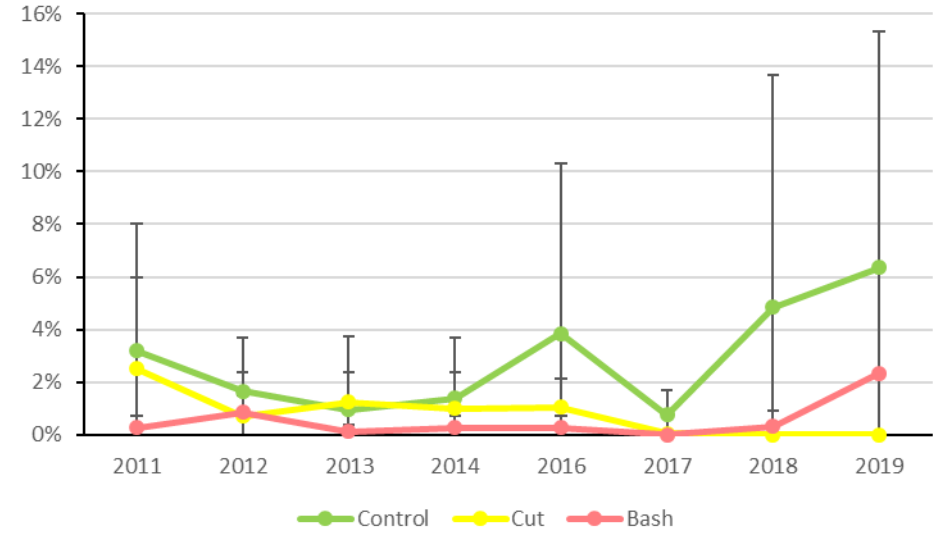


i

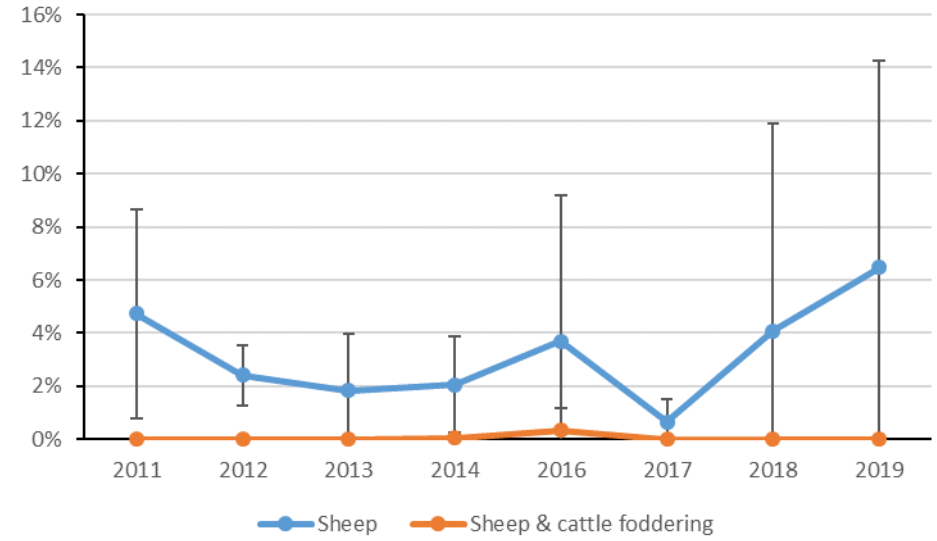


ii

Figure 136. *Poa pratensis* percentage cove at Ingram Farm, Northumberland r, 2011-2014 & 2016-19, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

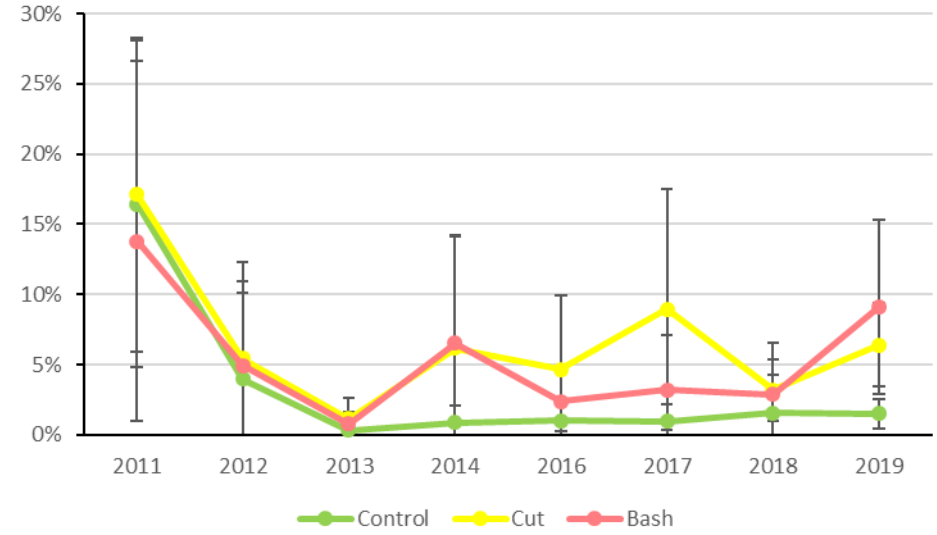


i

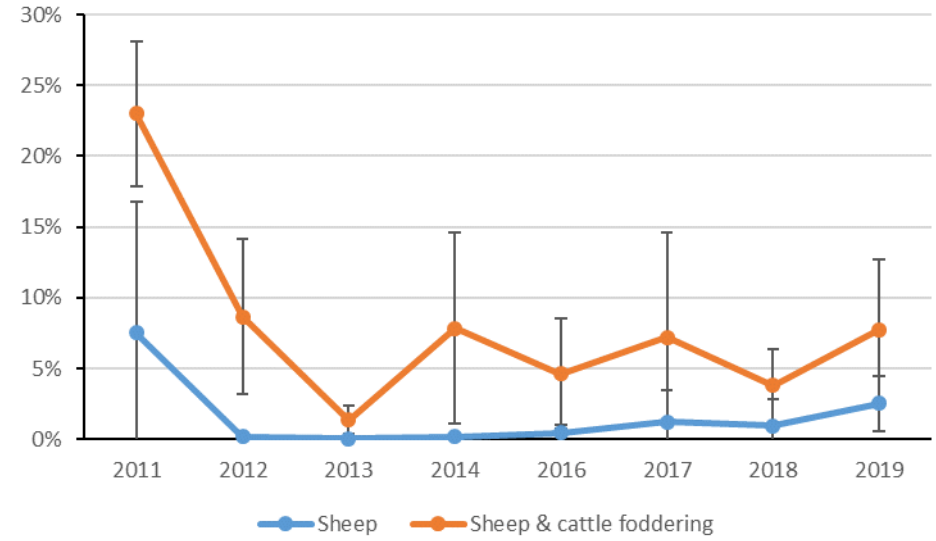


ii

Figure 137. *Digitalis purpurea* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

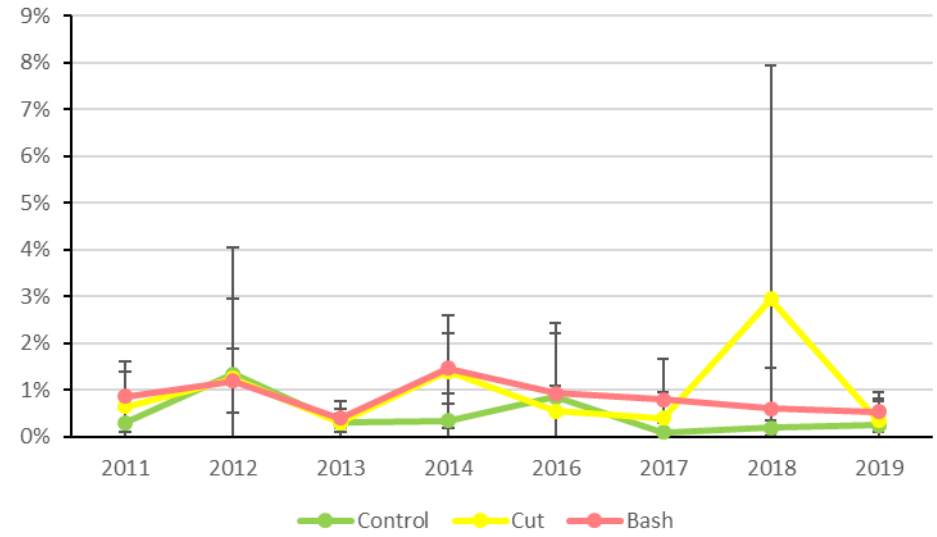


i

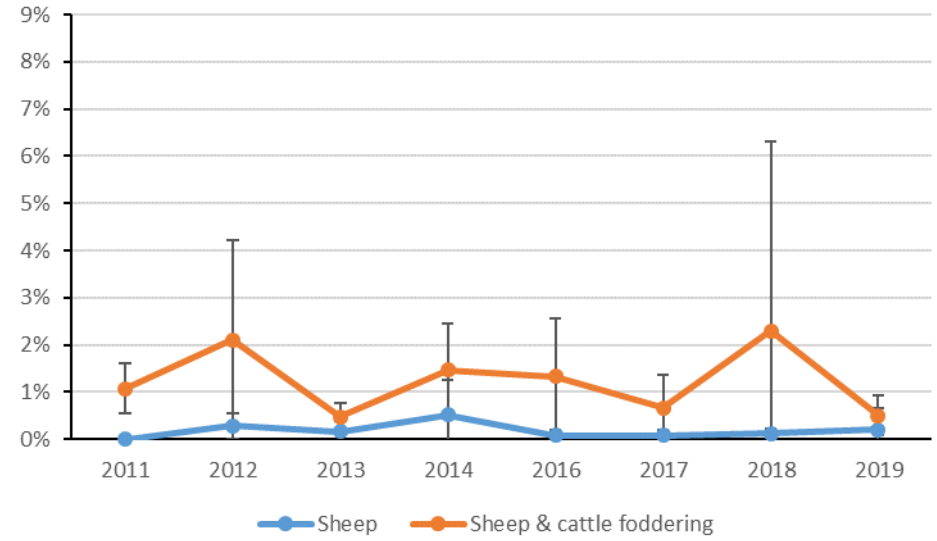


ii

Figure 138. *Galium saxatile* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

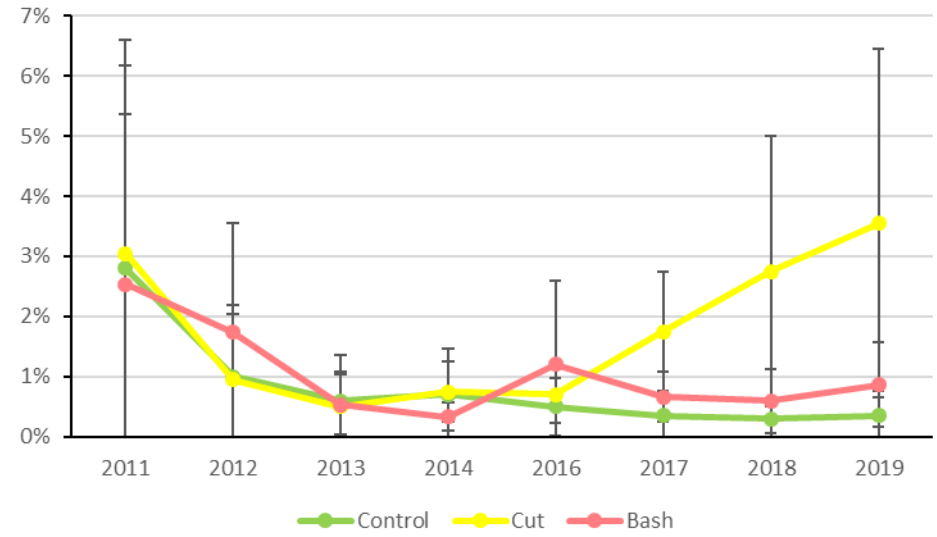


i

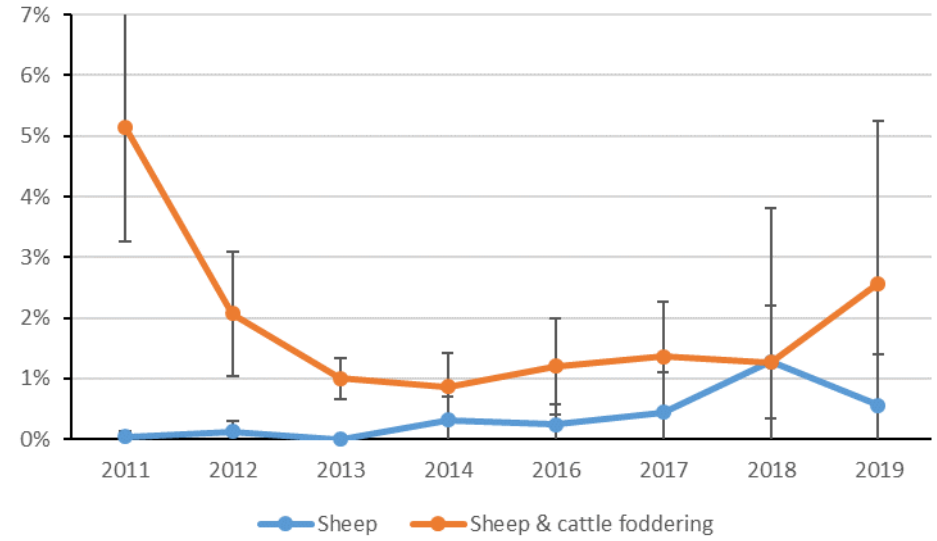


ii

Figure 139. *Potentilla erecta* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016



i



ii

Figure 140. *Rhytidiadelphus squarrosus* percentage cover at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

6.2.2 *PERCENTAGE COVER OF SELECTED SPECIES IN PHYSICAL/LIMING PLOTS, CHALLACOMBE FARM, DEVON 2016-2019*

Figures 141-143 (below) show the recorded mean (± standard deviation) cover of selected species according to treatment from 2016-2019.

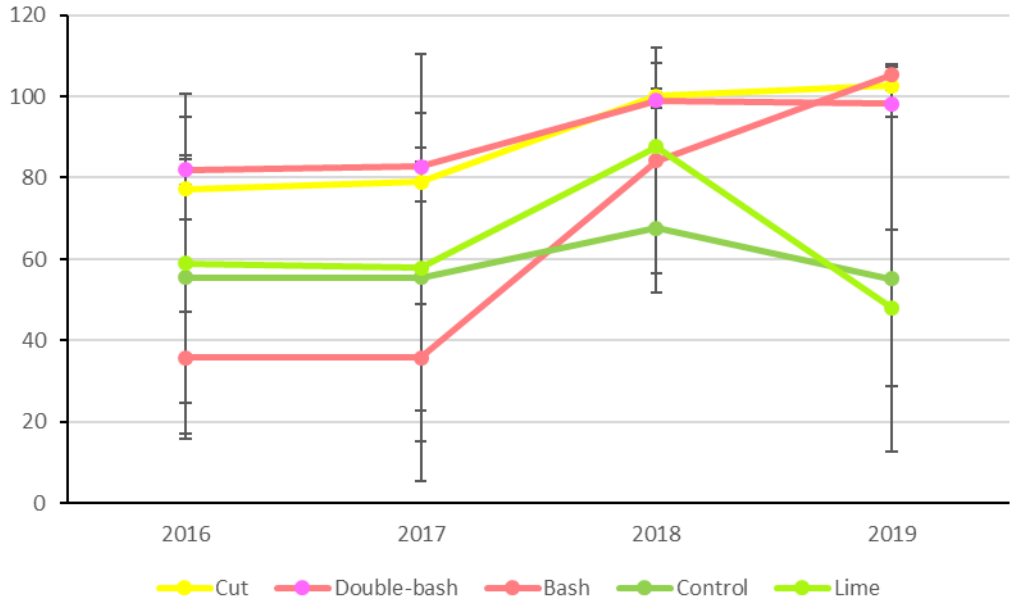


Figure 141. *Agrostis* dominated grass, percentage cover, 2016-2019, at Challacombe Farm, Devon, split by physical/liming treatments

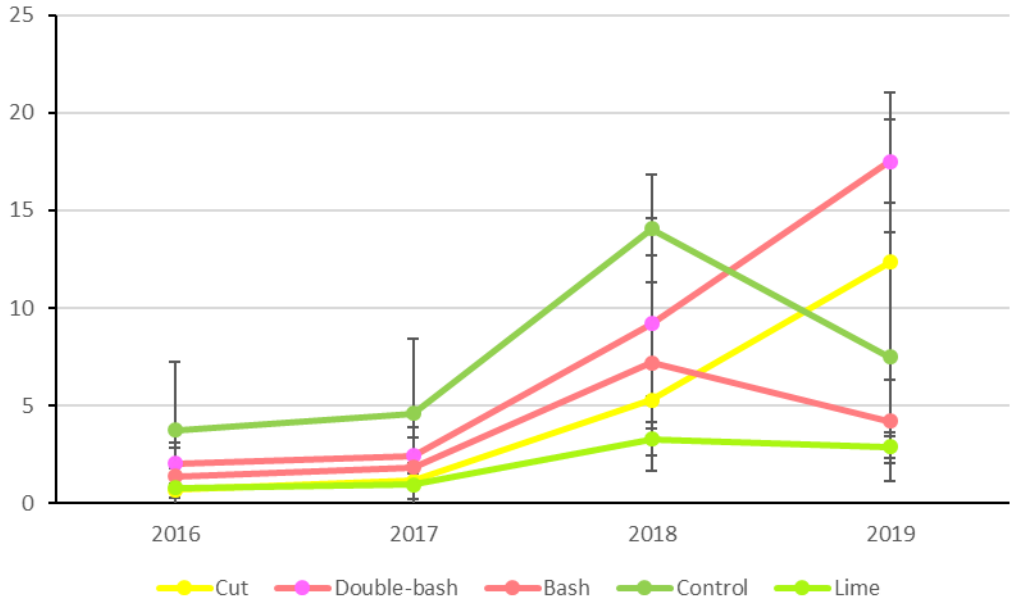


Figure 142. *Galium saxatile* percentage cover, 2016-2019, at Challacombe Farm, Devon, split by physical/liming treatments

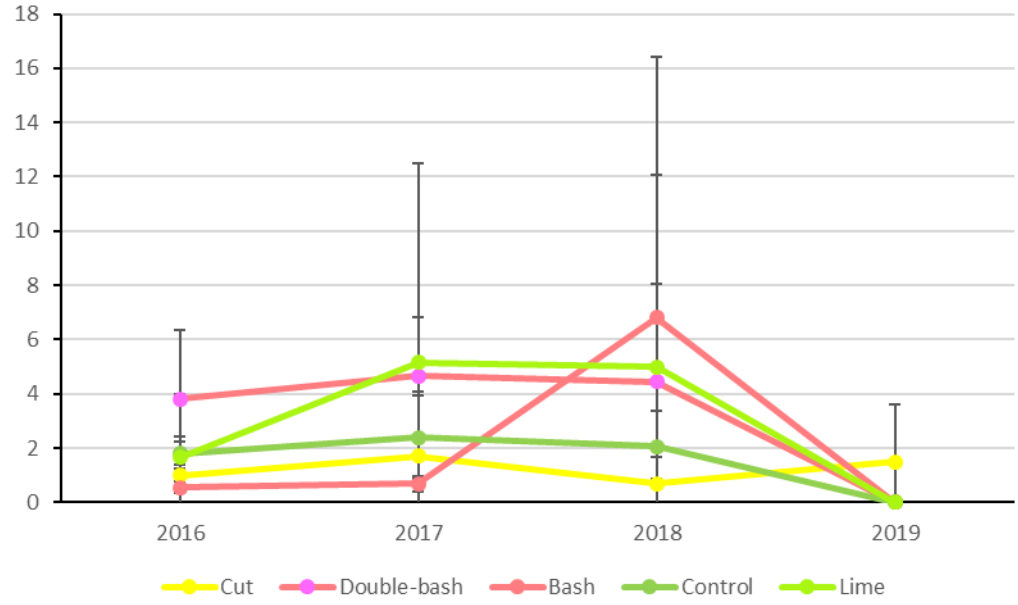


Figure 143. *Viola* spp. percentage cover, 2016-2019, at Challacombe Farm, Devon, split by physical/liming treatments

6.2.3 *PERCENTAGE COVER OF SELECTED SPECIES IN CHEMICAL TREATMENT PLOTS, CHALLACOMBE FARM, DEVON 2017-2019*

Figures 144-147 (below) show the recorded mean (± standard deviation) cover of selected species according to treatment from 2017-2019. Species cover data other than *Pteridium aquilinum* were not collected in the baseline year (2016).

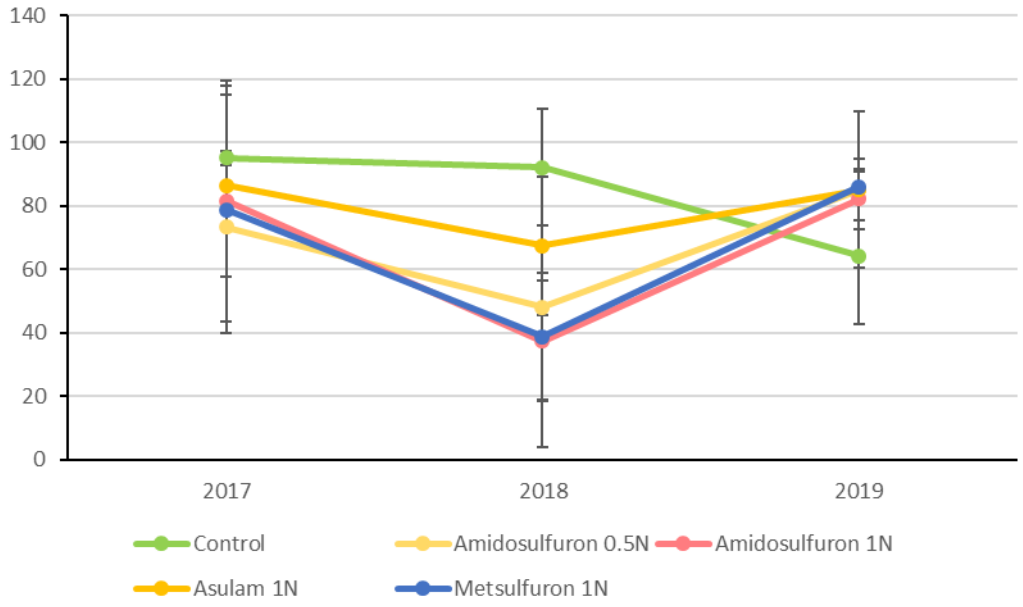


Figure 144. *Agrostis* dominated grass, percentage cover, 2017-2019, at Challacombe Farm, Devon, split by chemical treatments

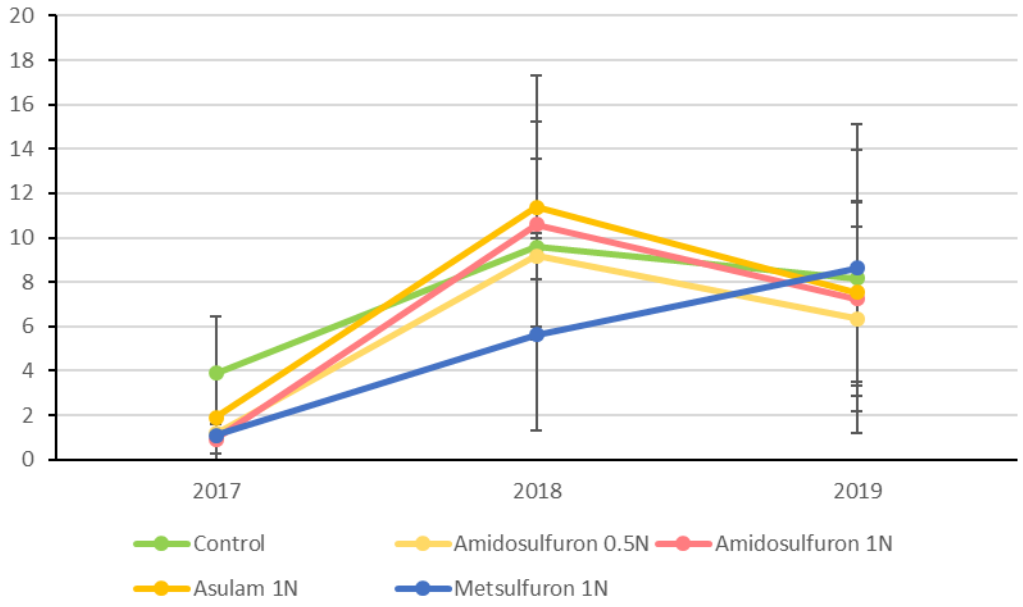


Figure 145. *Viola* spp. percentage cover, 2017-2019, at Challacombe Farm, Devon, split by chemical treatments

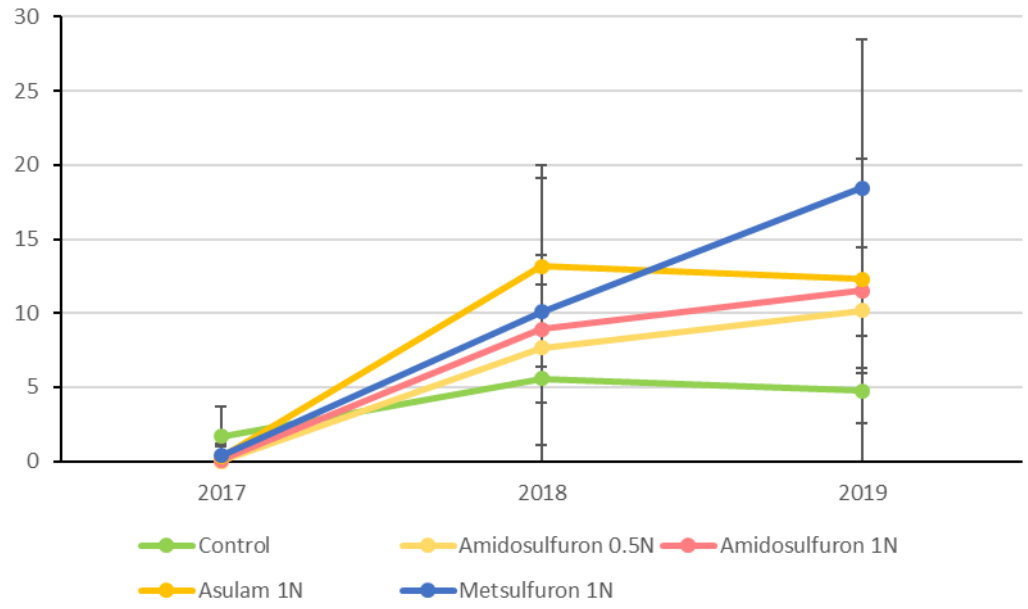


Figure 146. *Galium saxatile* percentage cover, 2017-2019, at Challacombe Farm, Devon, split by chemical treatments

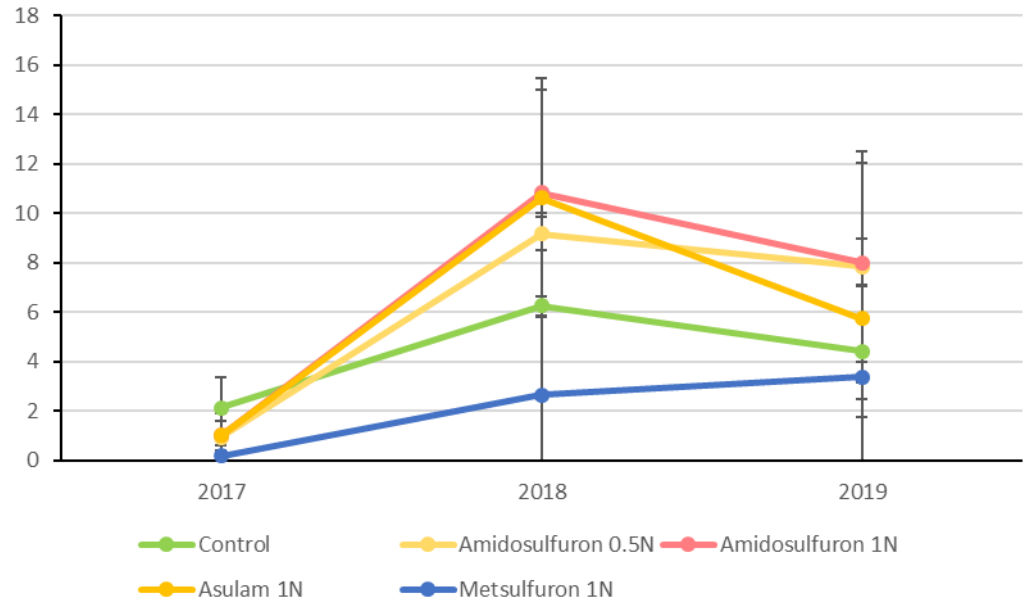


Figure 147. *Potentilla erecta* percentage cover, 2017-2019, at Challacombe Farm, Devon, split by chemical treatments

6.2.4 *PERCENTAGE COVER OF SELECTED SPECIES IN CHEMICAL TREATMENT PLOTS, FAWDON FARM, NORTHUMBERLAND 2017-2019*

Figures 148-149 (below) show the recorded mean (± standard deviation) cover of selected species according to treatment from 2017-2019. Species cover data other than *Pteridium aquilinum* were not collected in the baseline year (2016).

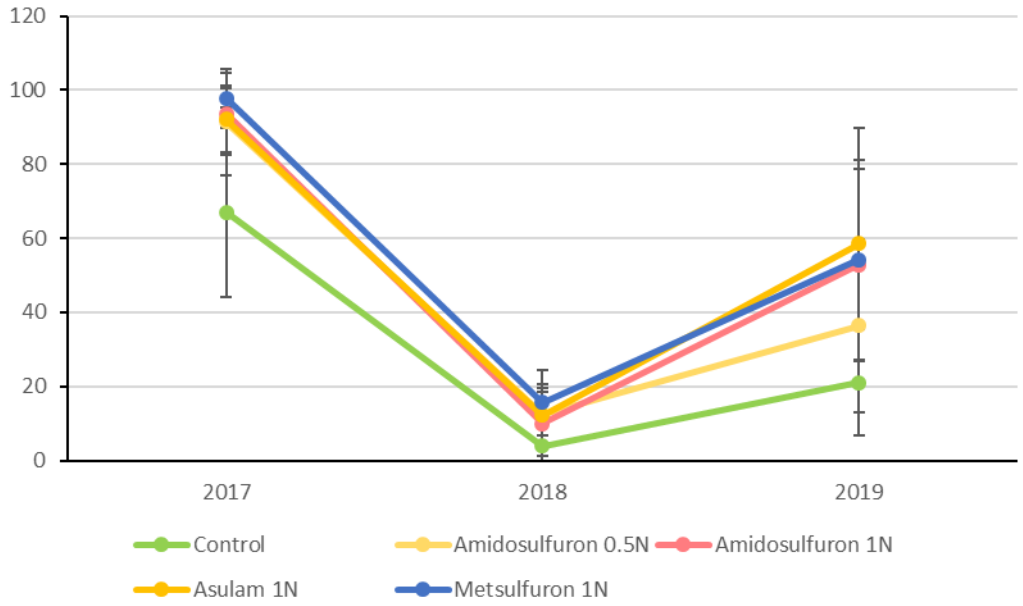


Figure 148. *Arrhenatherum* dominated grass percentage cover, 2017-2019, at Fawdon Farm, Northumberland, split by chemical treatments

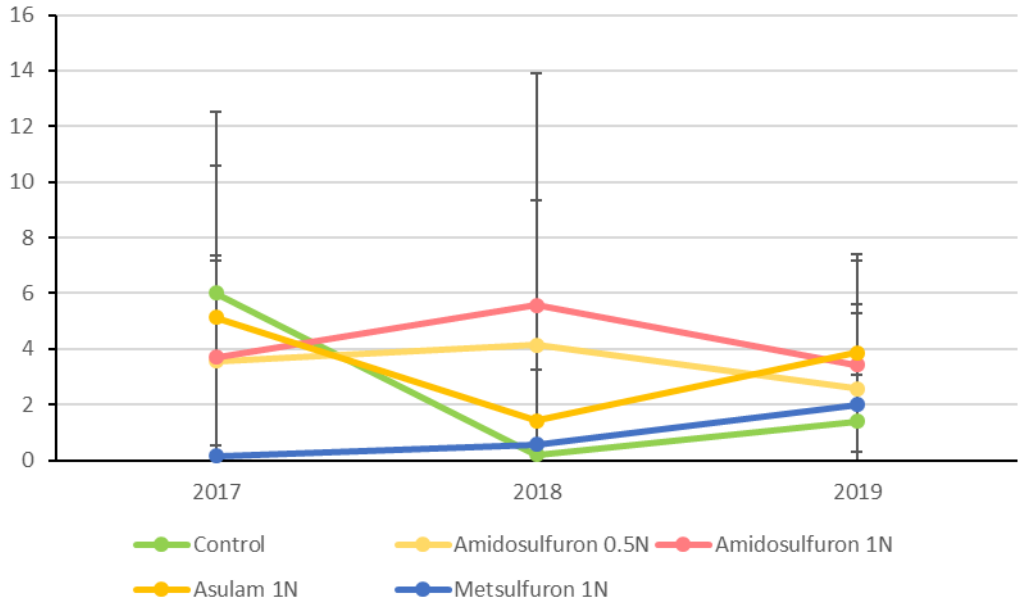


Figure 149. *Potentilla erecta* percentage cover, 2017-2019, at Fawdon Farm, Northumberland, split by chemical treatments

```
        Pearson's Chi-squared test

data:  Matriz
X-squared = 110.32, df = 3, p-value < 2.2e-16

            Comparison   p.Chisq p.adj.Chisq
1        Control : Cut  1.22e-13    3.66e-13
2       Control : Bash  2.08e-04    2.50e-04
3 Control : Double-bash 2.20e-02    2.20e-02
4           Cut : Bash  8.83e-05    1.32e-04
5     Cut : Double-bash 2.33e-19    1.40e-18
6    Bash : Double-bash 1.34e-08    2.68e-08
```

Table 59. Chi-square test of 2016 ground-mapped extent of full bracken cover with vigour score 7 or above, compared between treatments on Ewe Hill (no winter cattle foddering), Ingram Farm, Northumberland

```
        Pearson's Chi-squared test

data:  Matriz
X-squared = 43.72, df = 2, p-value = 3.209e-10

      Comparison  p.Chisq p.adj.Chisq
1  Control : Cut 4.75e-09    1.43e-08
2 Control : Bash 5.49e-01    5.49e-01
3     Cut : Bash 2.41e-07    3.62e-07
```

Table 60. Chi-square test of 2016 ground-mapped extent of full bracken cover with vigour score 7 or above, compared between treatments on Wether Hill (winter cattle foddering), Ingram Farm, Northumberland

```
        Pearson's Chi-squared test

data:  Matriz
X-squared = 189.01, df = 3, p-value < 2.2e-16

            Comparison   p.Chisq p.adj.Chisq
1        Control : Cut  2.46e-23    7.38e-23
2       Control : Bash  1.02e-05    1.22e-05
3 Control : Double-bash 3.78e-02    3.78e-02
4           Cut : Bash  6.72e-39    4.03e-38
5     Cut : Double-bash 2.25e-16    4.50e-16
6    Bash : Double-bash 2.23e-10    3.35e-10
```

Table 61. Chi-square test of 2019 ground-mapped extent of full bracken cover with vigour score 7 or above, compared between treatments on Ewe Hill (no winter cattle foddering), Ingram Farm, Northumberland

```
        Pearson's Chi-squared test

data:  Matriz
X-squared = 29.144, df = 2, p-value = 4.694e-07

      Comparison  p.Chisq p.adj.Chisq
1  Control : Cut 1.04e-07    3.12e-07
2 Control : Bash 1.44e-01    1.44e-01
3     Cut : Bash 5.77e-05    8.66e-05
```

Table 62. Chi-square test of 2019 ground-mapped extent of full bracken cover with vigour score 7 or above, compared between treatments on Wether Hill (winter cattle foddering), Ingram Farm, Northumberland

```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 8.392, df = 1, p-value = 0.003769
```

Table 63. Chi-square test of 2016 ground-mapped extent of full bracken cover with vigour score 7 or above, Control treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 1.1289, df = 1, p-value = 0.288
```

Table 64. Chi-square test of 2016 ground-mapped extent of full bracken cover with vigour score 7 or above, Cut treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 3.0368e-30, df = 1, p-value = 1
```

Table 65. Chi-square test of 2016 ground-mapped extent of full bracken cover with vigour score 7 or above, Bash treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 34.455, df = 1, p-value = 4.362e-09
```

Table 66. Chi-square test of 2019 ground-mapped extent of full bracken cover with vigour score 7 or above, Control treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

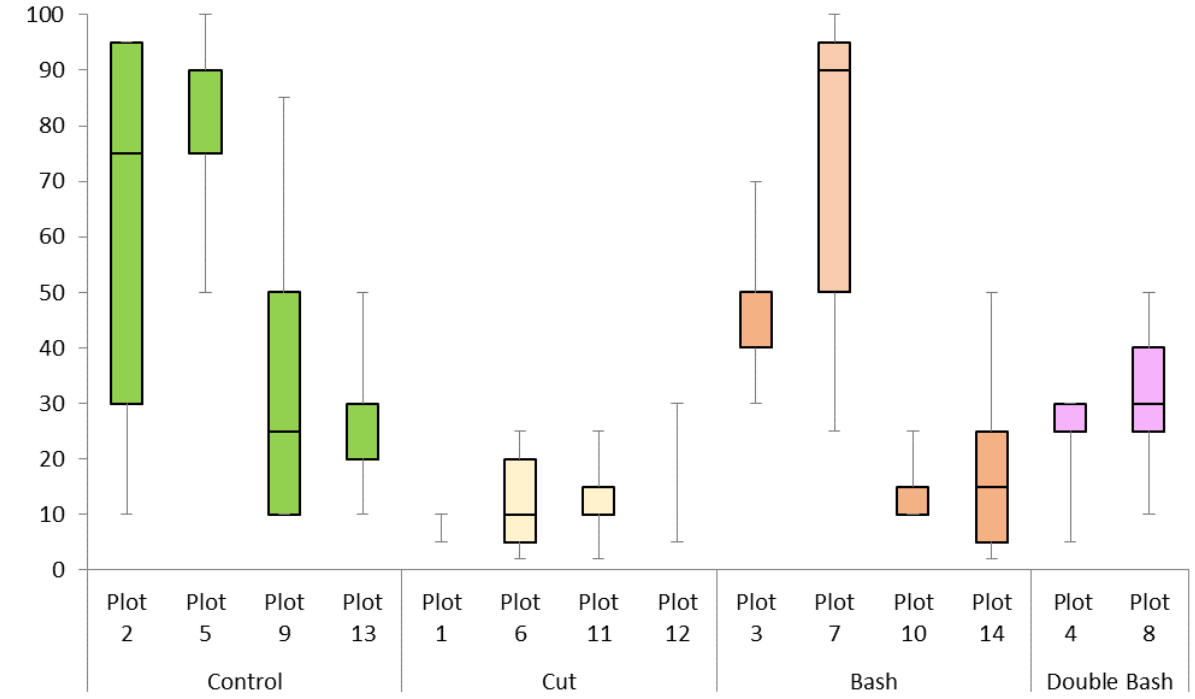
```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 0.016869, df = 1, p-value = 0.8967
```

Table 67. Chi-square test of 2019 ground-mapped extent of full bracken cover with vigour score 7 or above, Cut treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

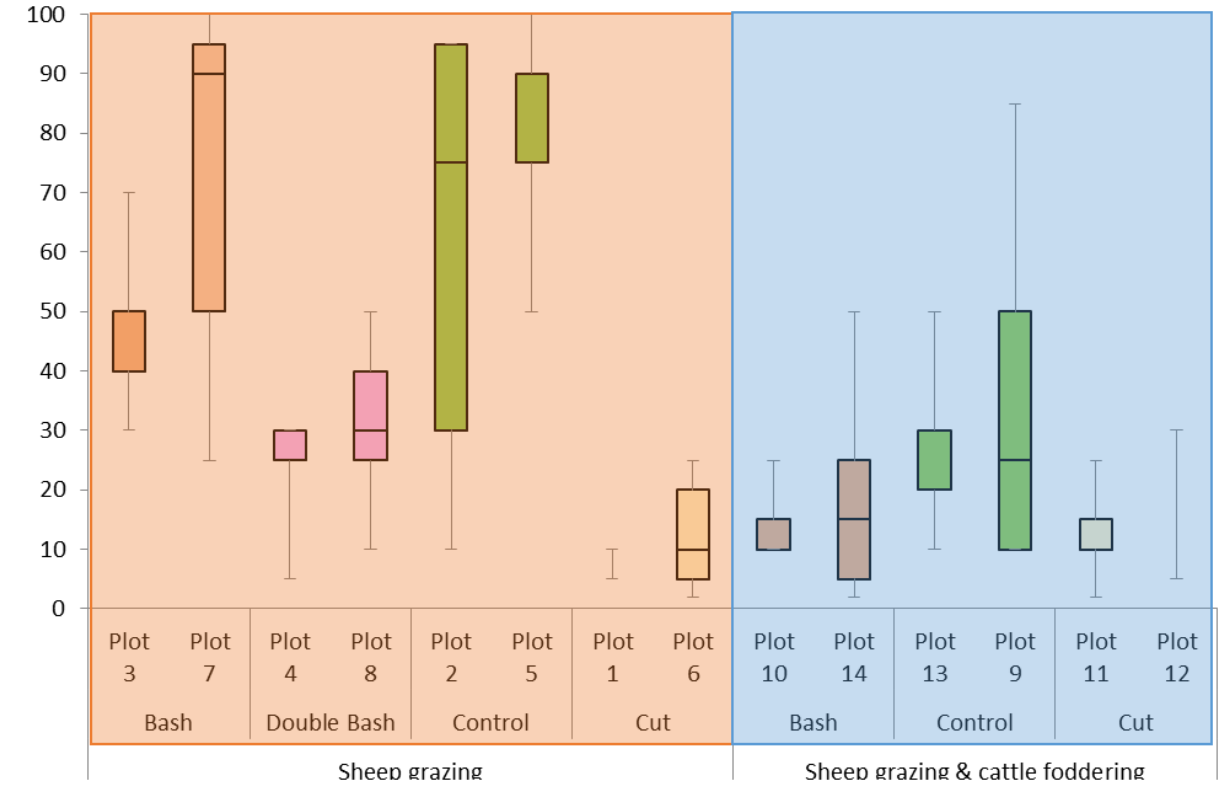
```
Pearson's Chi-squared test with Yates' continuity correction

data:  Matriz
X-squared = 116.95, df = 1, p-value < 2.2e-16
```

Table 68. Chi-square test of 2019 ground-mapped extent of full bracken cover with vigour score 7 or above, Bash treatment Wether Hill (winter cattle foddering) vs. Ewe Hill (no winter foddering), Ingram Farm, Northumberland

6.4 QUADRAT-BASED ASSESSMENTS OF DAMAGE TO THE GROUND

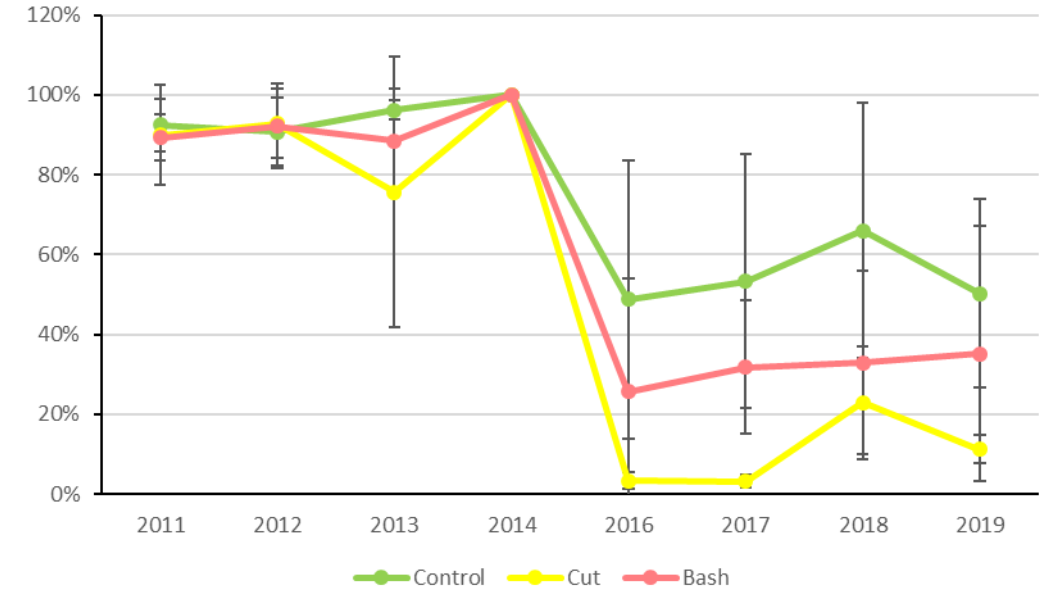


i

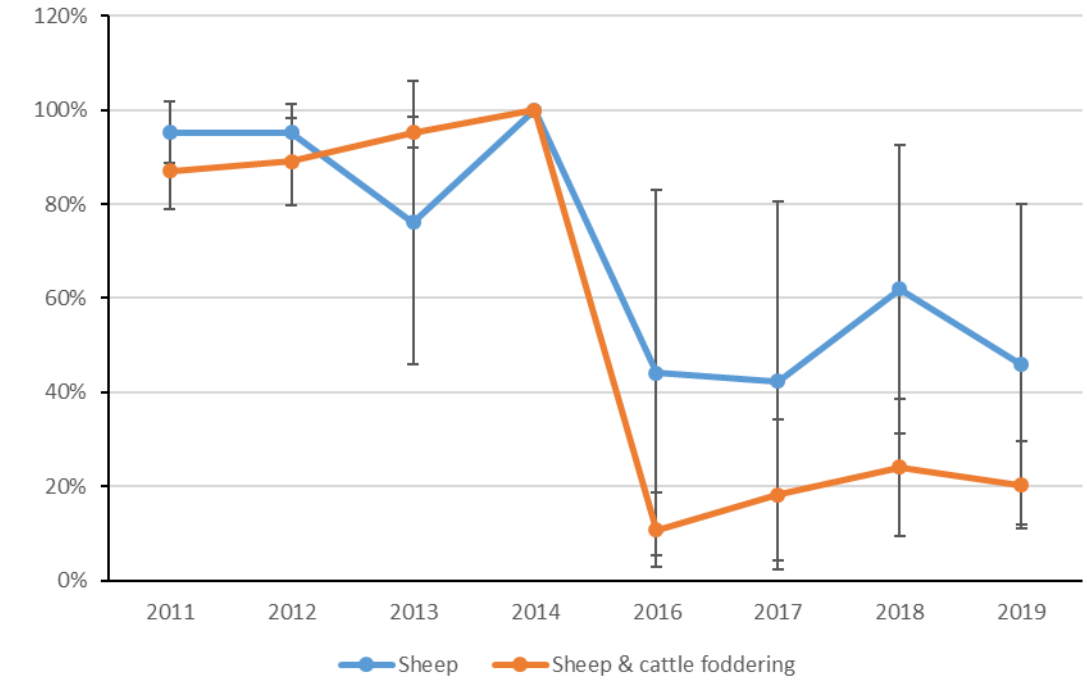


ii

Figure 150. Median (min, Q1, Q3, max) litter cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland



i

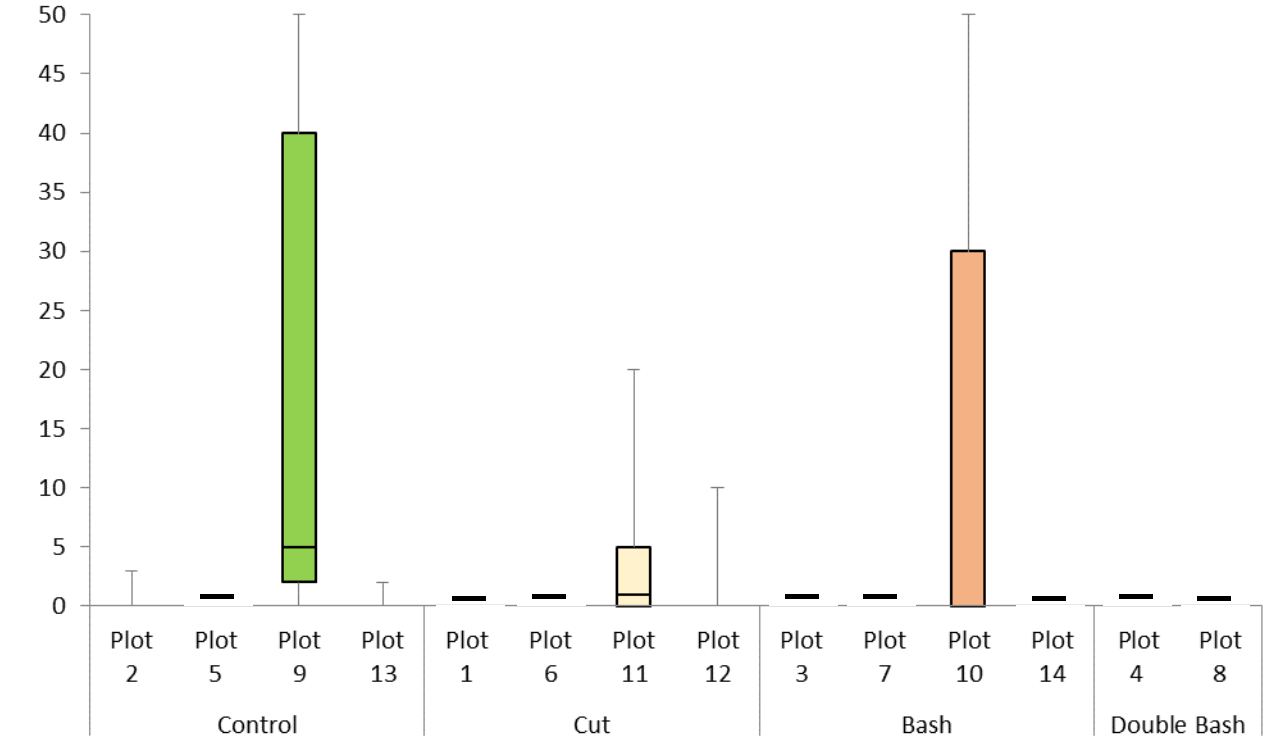


ii

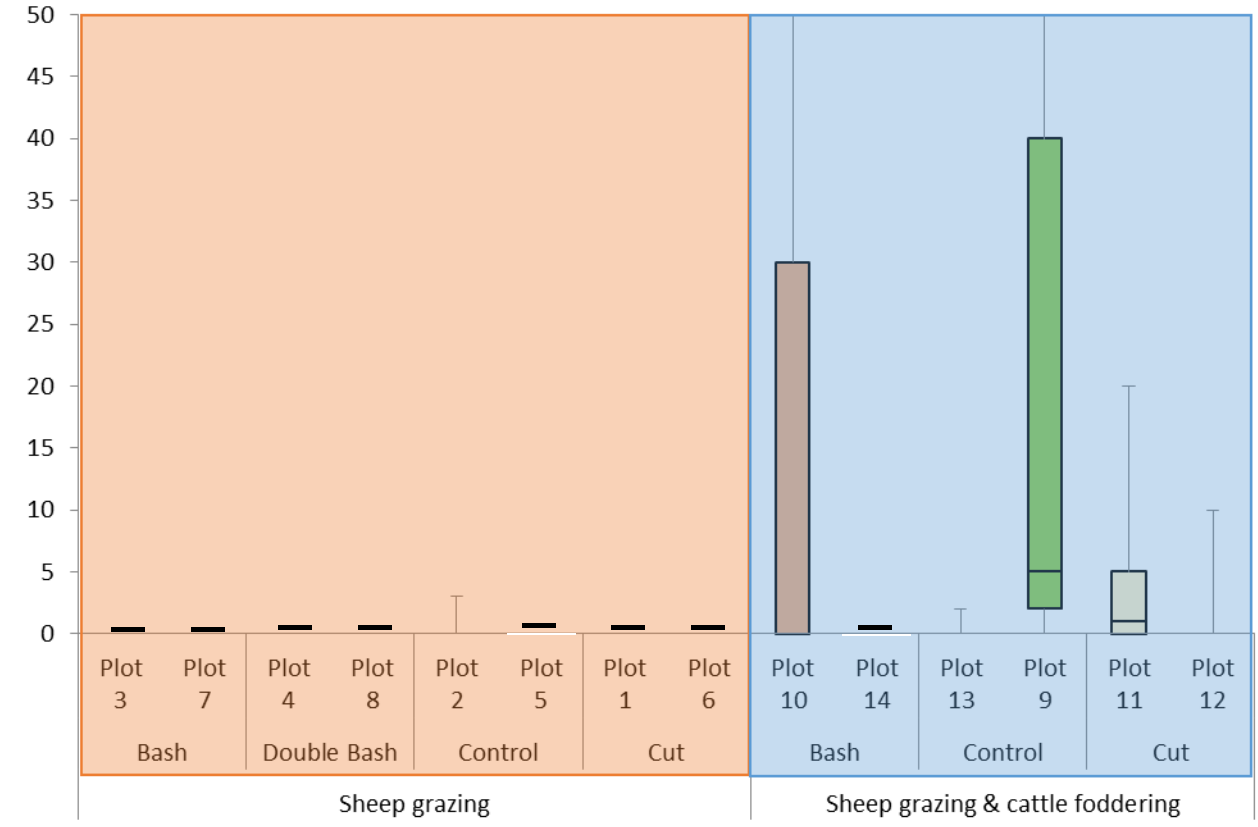
Figure 151. Mean (± standard deviation) litter cover (%) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  15461    7731  17.395 2.71e-06 ***
Grazing      1   9550    9550  21.489 3.18e-05 ***
Plot         7   9283    1326   2.984   0.0119 *
Residuals   44  19554     444

Significant pairwise comparisons:
Mechanical treatment
                        diff       lwr        upr     p adj
Cut-Control         -39.05000 -55.21907 -22.880928 0.0000016
Single Bash-Cut      23.93333   6.46874  41.397927 0.0050095

Grazing treatment
                       diff      lwr        upr    p adj
Sheep/Cattle-Sheep -26.16778 -37.67292 -14.66264 3.76e-05
```

Table 69. ANOVA & Tukey range test on litter cover 2019 (%) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i

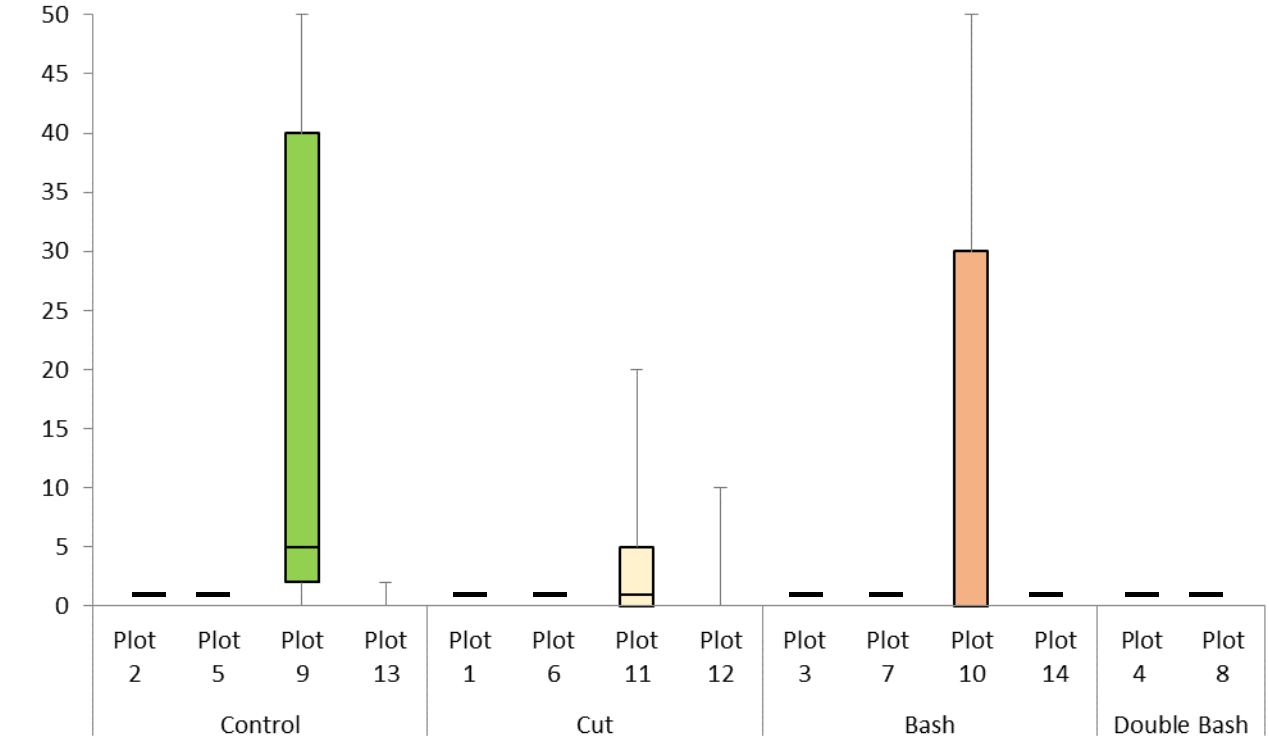


ii

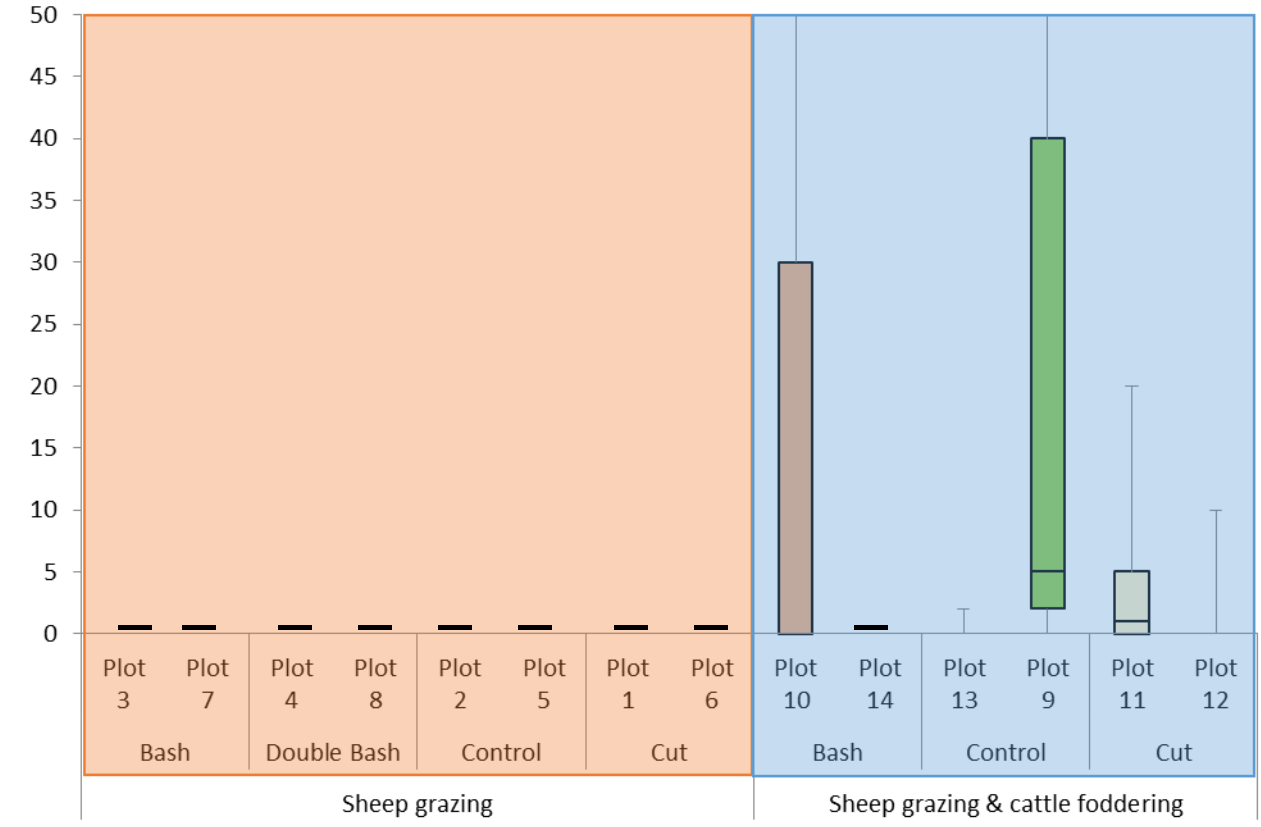
Figure 152. Median (min, Q1, Q3, max) bare ground cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Mechanical	2	0.0281	0.01406	0.463	0.63230	
Grazing	1	0.2745	0.27453	9.042	0.00435	**
Plot	7	0.5110	0.07300	2.404	0.03567	*
Residuals	44	1.3360	0.03036			

Table 70. ANOVA test on arcsine transformation of bare ground cover 2019 (%) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland



i

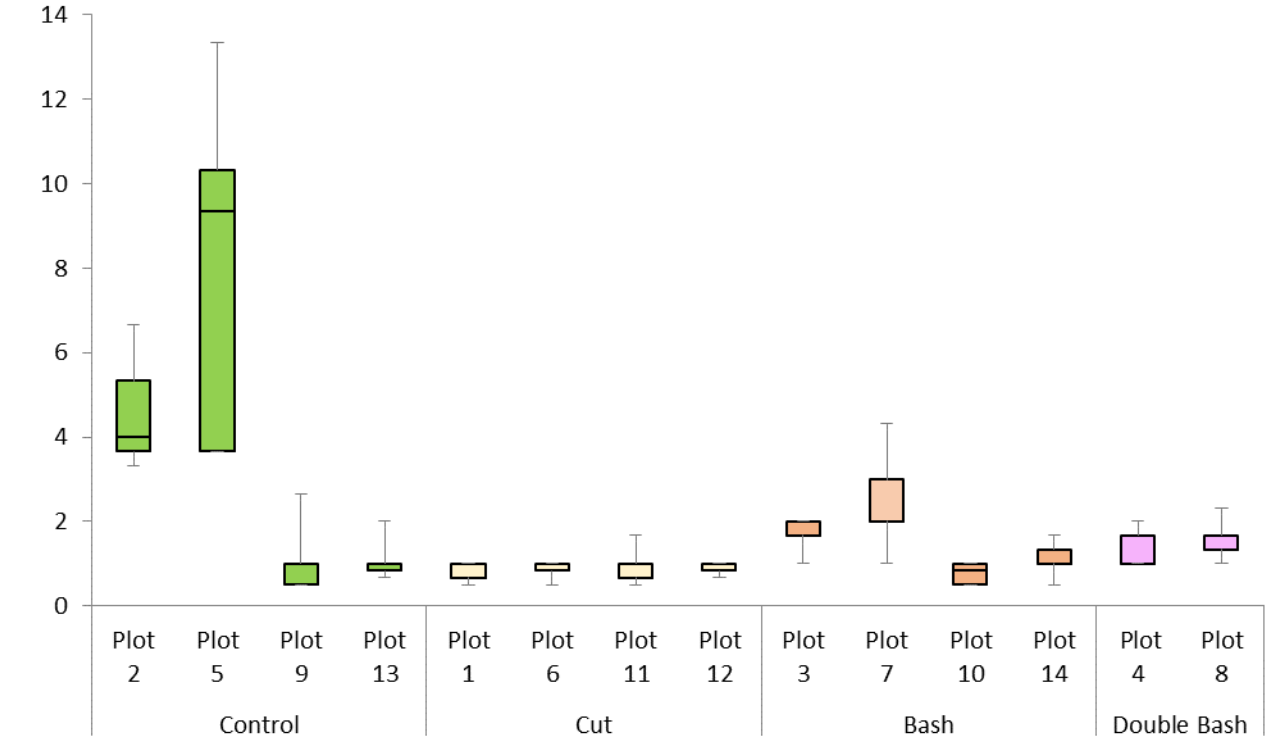


ii

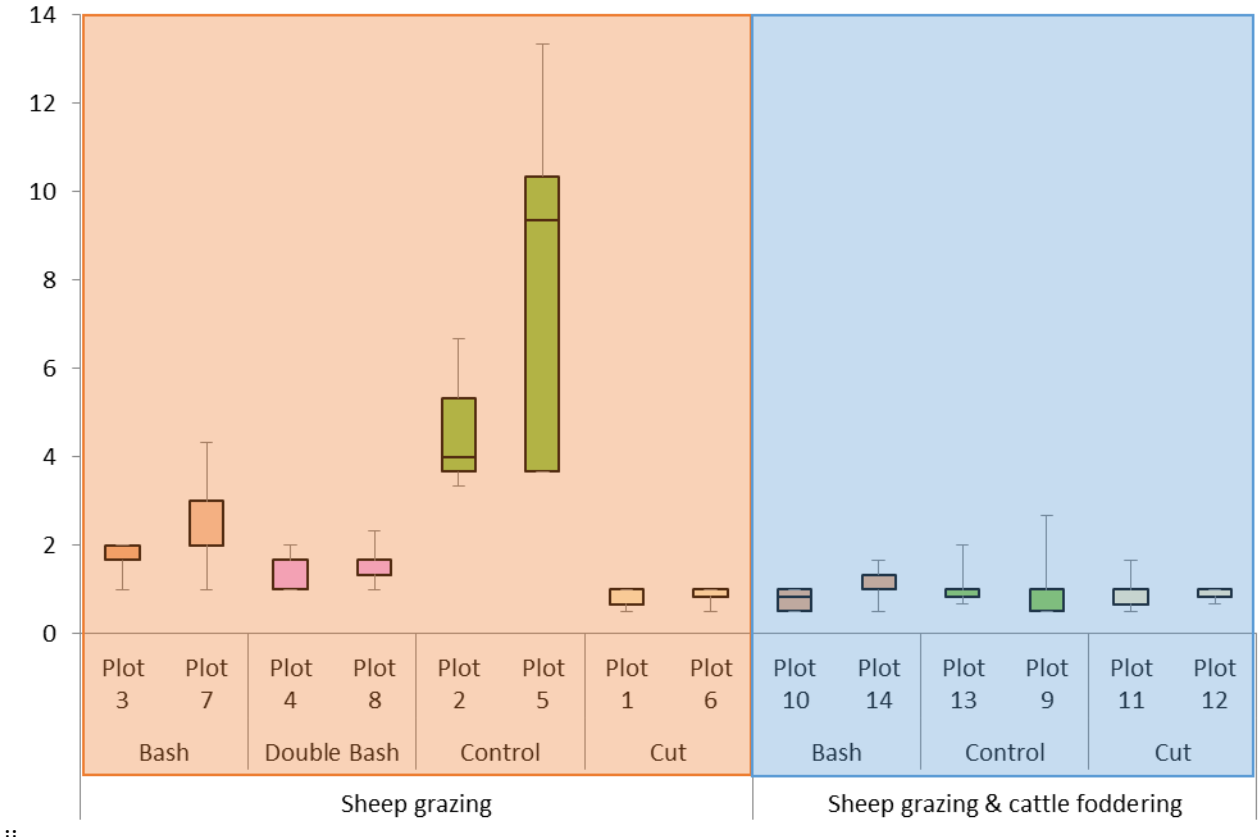
Figure 153. Median (min, Q1, Q3, max) disturbed ground cover 2019 (%), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland

```
          Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   2 0.0209 0.01046   0.351 0.70615
Grazing      1 0.3001 0.30008  10.066 0.00275 **
Plot         7 0.5154 0.07362   2.470 0.03150 *
Residuals   44 1.3117 0.02981
```

Table 71. ANOVA test on arcsine transformation of disturbed ground cover 2019 (%) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland

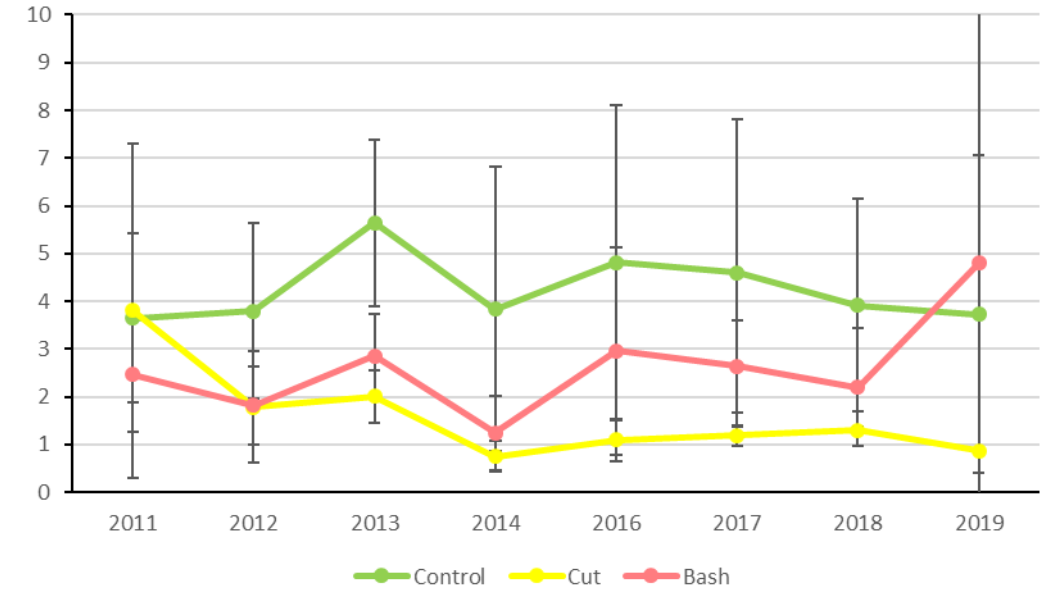


i

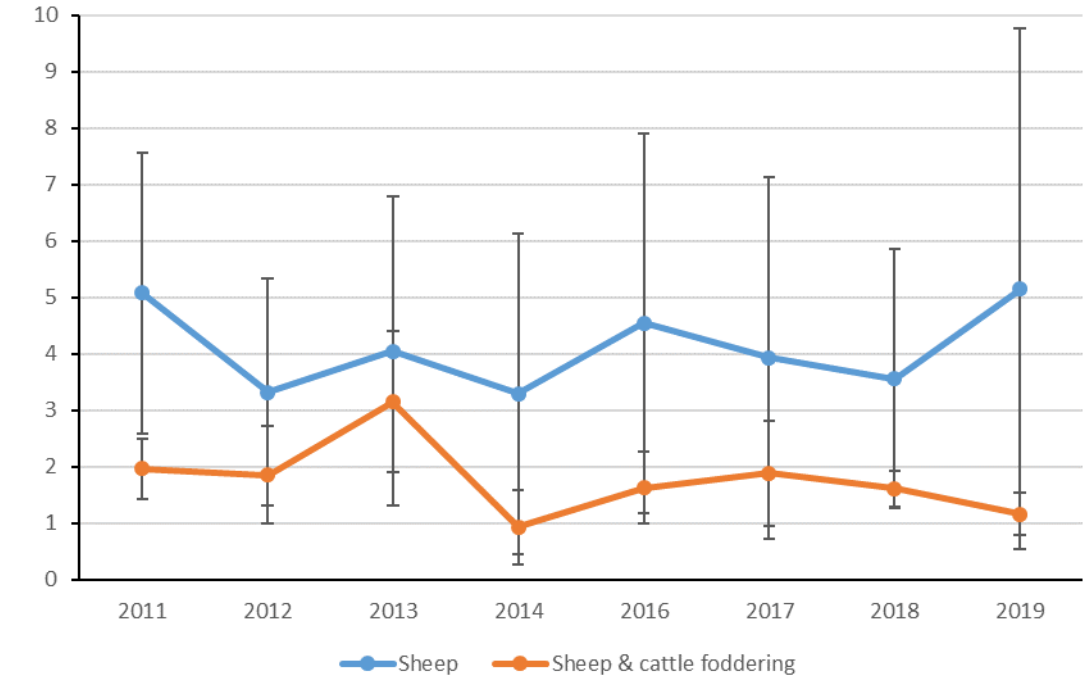


ii

Figure 154. Median (min, Q1, Q3, max) litter depth 2019 (cm), arranged according to mechanical treatment (i) & grazing treatment (ii) at Ingram Farm, Northumberland



i



ii

Figure 155. Mean litter depth (cm) at Ingram Farm, Northumberland, 2011-2014 & 2016-2019, by mechanical treatment (i) & grazing treatment (ii). Excludes the Double-Bash treatment plots & Bash plot established in 2016

```
           Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  89.60   44.80  21.029 3.90e-07 ***
Grazing      1  72.17   72.17  33.876 6.20e-07 ***
Plot         7 102.03   14.58   6.841 1.65e-05 ***
Residuals   44  93.74    2.13

Significant pairwise comparisons:
Mechanical treatment
                     diff        lwr       upr     p adj
Cut-Control         -2.858 -3.9775088 -1.738491 0.0000005
Single Bash-Control -2.281 -3.4902077 -1.071792 0.0001128

Grazing treatment
                     diff       lwr       upr p adj
Sheep/Cattle-Sheep -2.2748 -3.071389 -1.478211 8e-07
```

Table 72. ANOVA & Tukey range test on mean litter depth 2019 (cm) according to plot, mechanical treatment & grazing treatment at Ingram Farm, Northumberland

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Mechanical   2  1.764  0.8820   8.945 0.00144 **
Residuals   22  2.169  0.0986

Significant pairwise comparisons:
                           diff        lwr         upr     p adj
Double Bash-Control     -0.5912260 -0.9439886 -0.23846343 0.0010122
```

Table 73. ANOVA & Tukey test on arcsine transformation of mean litter cover (%) in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

```
            Df Sum Sq Mean Sq F value   Pr(>F)
Mechanical   2  138.5   69.26   13.42 0.000155 ***
Residuals   22  113.5    5.16

Significant pairwise comparisons:
                         diff       lwr       upr     p adj
Double Bash-Control     -4.900 -7.452119 -2.347881 0.0002303
Single Bash-Control     -4.599 -7.724694 -1.473306 0.0034705
```

Table 74. ANOVA & Tukey test of mean litter depth (cm) in quadrats at new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2019

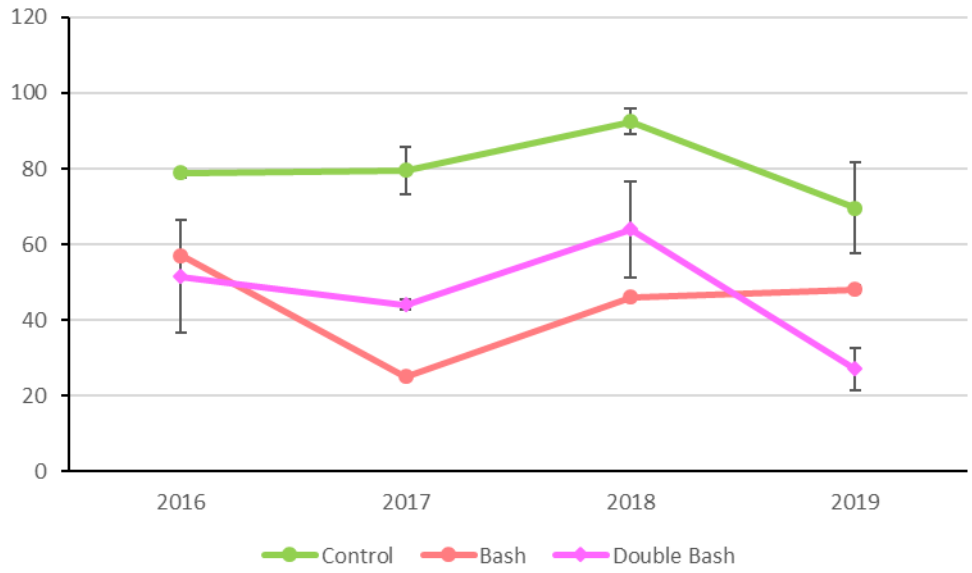


Figure 156. Mean (± standard deviation) litter cover (%) in new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

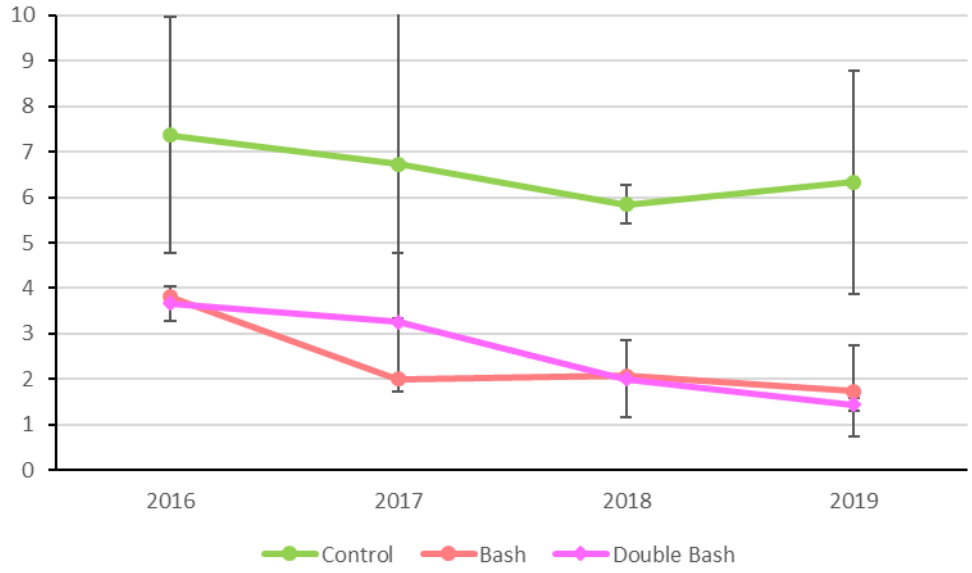


Figure 157. Mean (± standard deviation) litter depth (cm) in quadrats of new plots (3, 4 & 8) on Ewe Hill, Ingram Farm & mean of Control plots (2 & 5) on Ewe Hill, Ingram Farm, 2016-2019

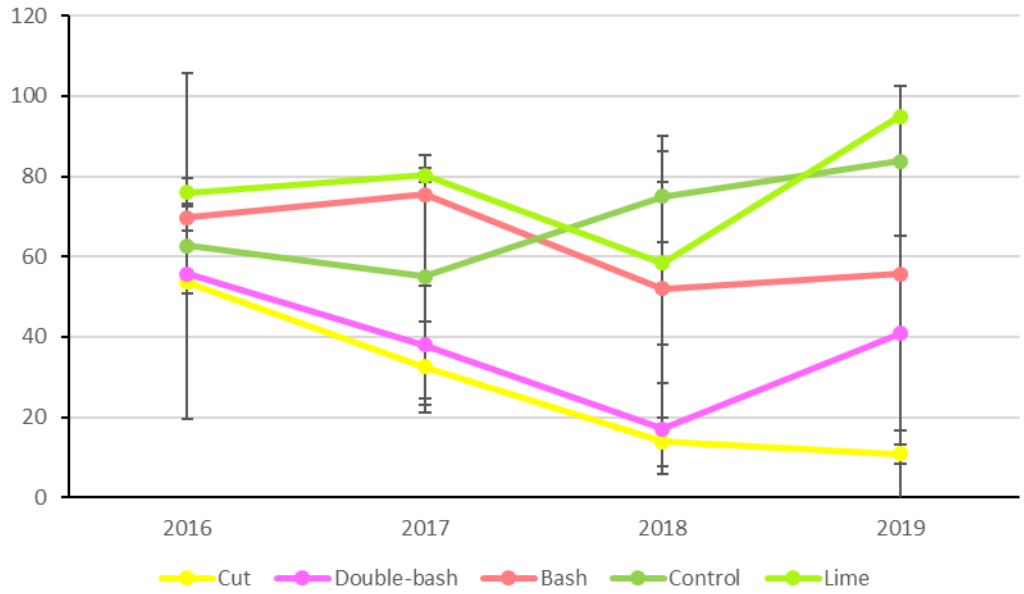


Figure 158. Mean (± standard deviation) litter cover (%) 2016-2019 at Challacombe Farm, Devon, split by mechanical & liming treatments

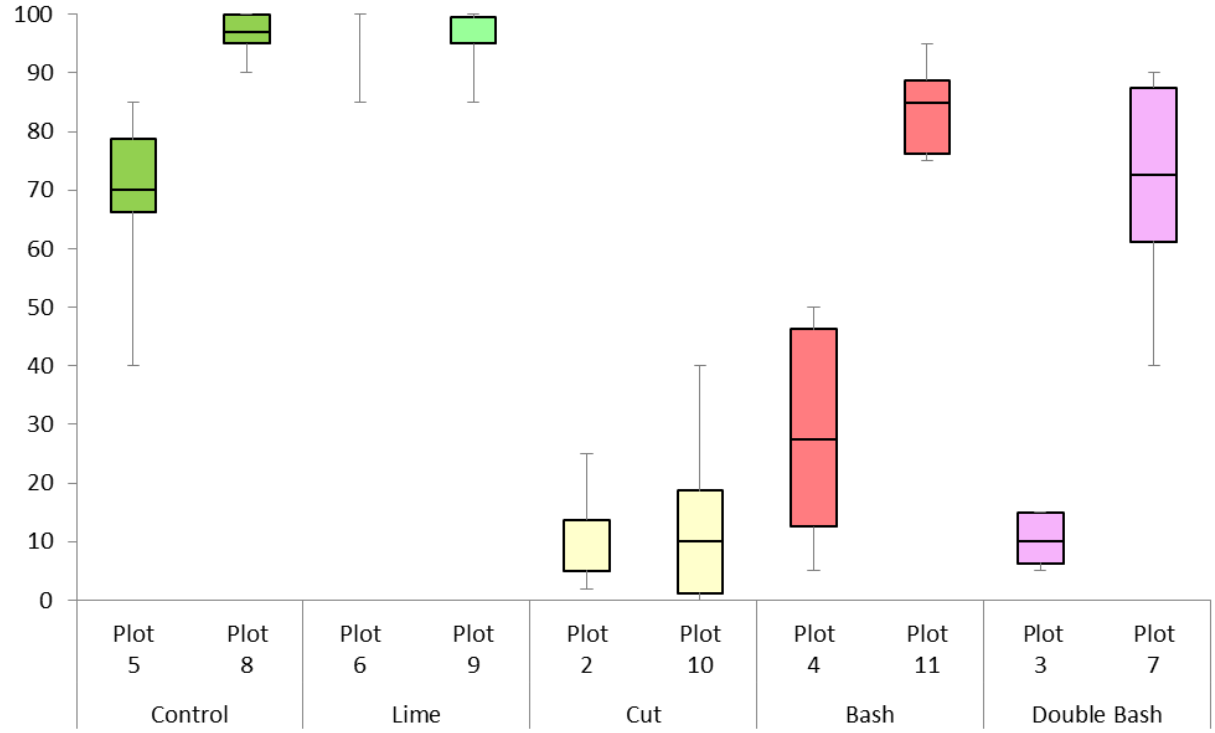


Figure 159. Median (min, Q1, Q3, max) litter cover 2019 (%), at Challacombe Farm, Devon, arranged according to mechanical & liming treatments

```
            Df Sum Sq Mean Sq F value Pr(>F)
Mechanical   4  90728   22682  201.81 <2e-16 ***
Plot         5  37549    7510   66.81 <2e-16 ***
Residuals   90  10116     112

Significant pairwise comparisons:
                        diff        lwr        upr     p adj
Control-Bash           27.95  18.617007  37.282993 0.0000000
Cut-Bash              -44.90 -54.232993 -35.567007 0.0000000
Double-bash-Bash      -14.75 -24.082993  -5.417007 0.0002822
Lime-Bash              39.15  29.817007  48.482993 0.0000000
Cut-Control           -72.85 -82.182993 -63.517007 0.0000000
Double-bash-Control   -42.70 -52.032993 -33.367007 0.0000000
Lime-Control           11.20   1.867007  20.532993 0.0104404
Double-bash-Cut        30.15  20.817007  39.482993 0.0000000
Lime-Cut               84.05  74.717007  93.382993 0.0000000
Lime-Double-bash       53.90  44.567007  63.232993 0.0000000
```

Table 75. ANOVA & Tukey range test on litter cover 2019 (%) in mechanical & liming treatment plots at Challacombe Farm, Devon

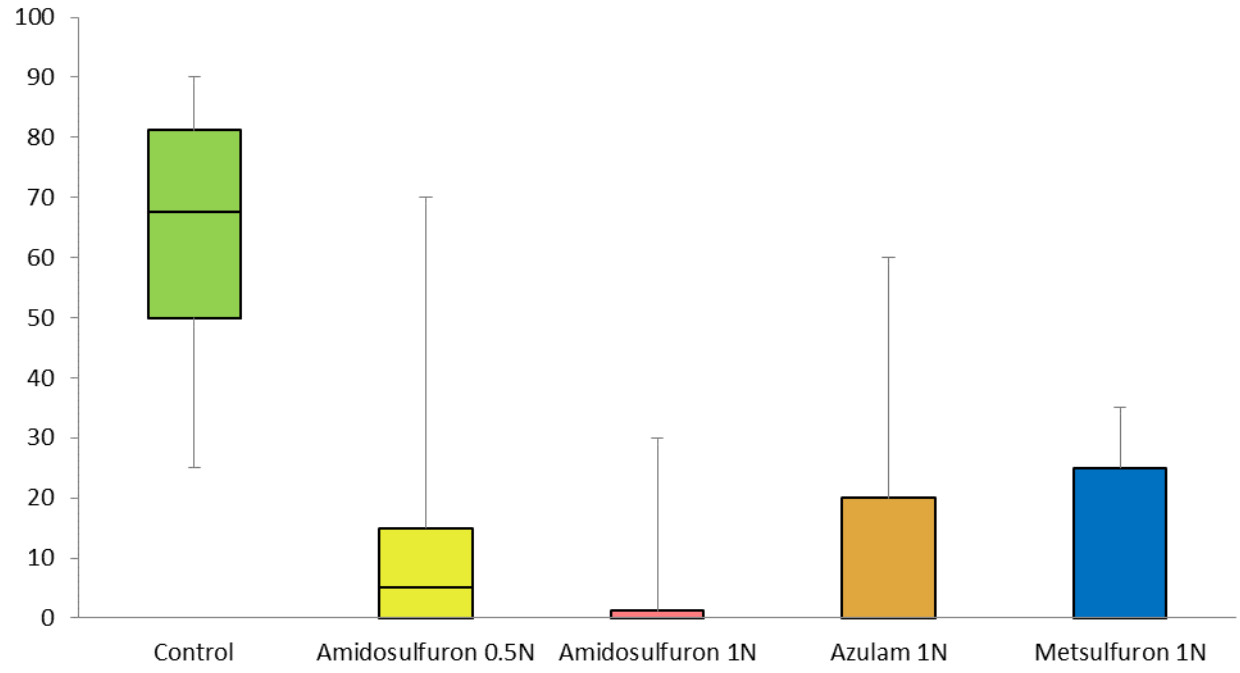


Figure 160. Median (min, Q1, Q3, max) litter cover 2019 (%), at Challacombe Farm, Devon, arranged according to chemical treatments

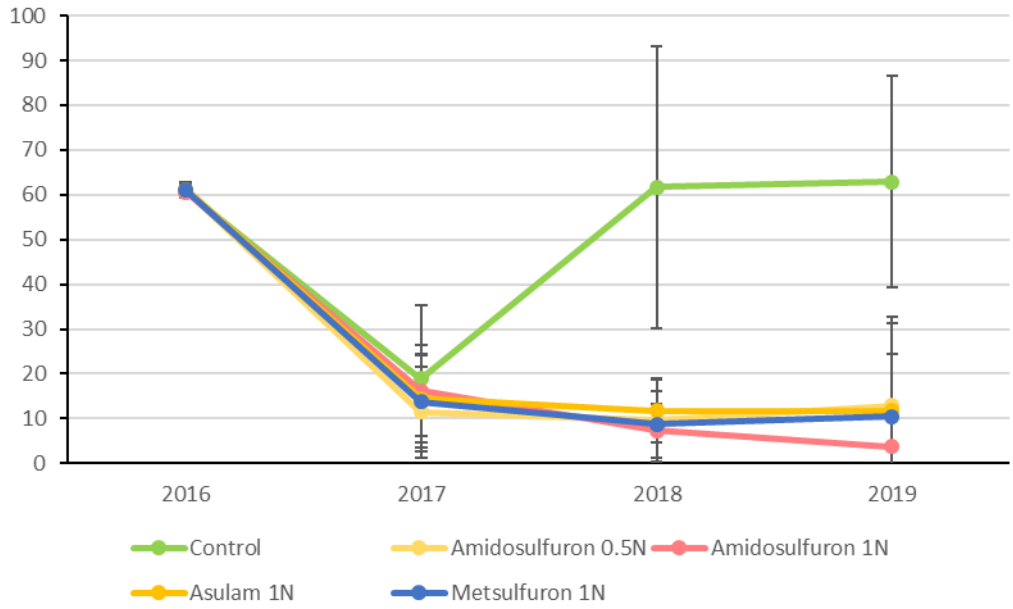


Figure 161. Mean (± standard deviation) litter cover (%) 2016-2019 at Challacombe Farm, Devon, split by chemical treatments

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Chemical	4	3.641	0.9103	21.36	1.54e-10	***
Residuals	53	2.259	0.0426			

Significant pairwise comparisons:

	diff	lwr	upr	p adj
Control-Amidosulfuron 0.5N	0.579022024	0.3410341	0.8170099	0.0000001
Control-Amidosulfuron 1N	0.676935709	0.4389478	0.9149236	0.0000000
Control-Asulam 1N	0.592032489	0.3486959	0.8353691	0.0000001
Metsulfuron 1N-Control	-0.599588663	-0.8429253	-0.3562520	0.0000001

Table 76. ANOVA & Tukey range test on arcsine transformed litter cover 2019 (%) in chemical treatment plots at Challacombe Farm, Devon

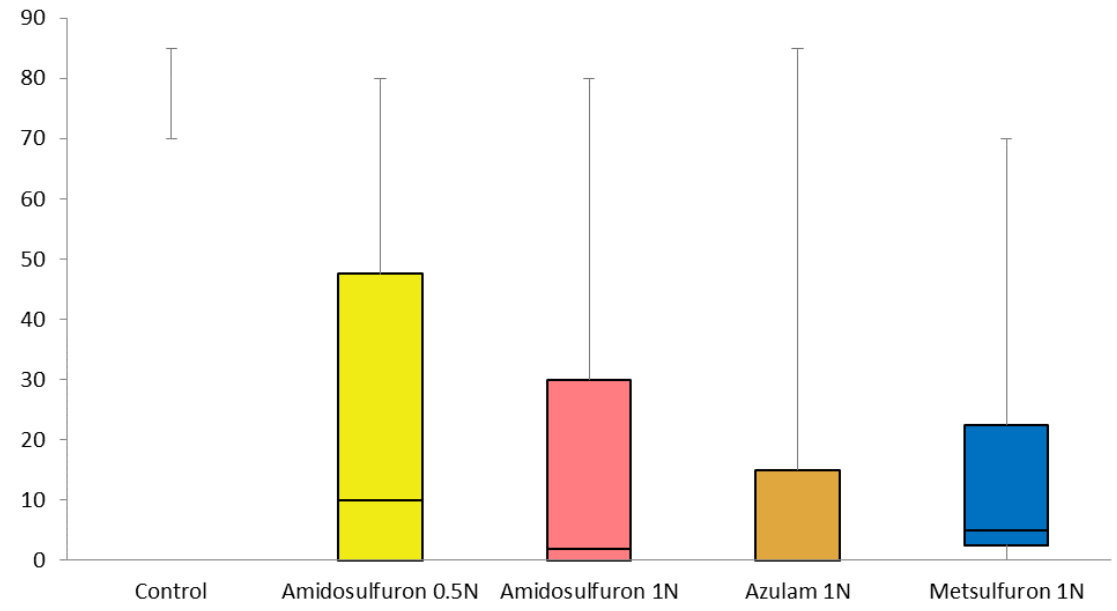


Figure 162. Median (min, Q1, Q3, max) litter cover 2019 (%), at Fawdon Farm, Northumberland, arranged according to chemical treatments

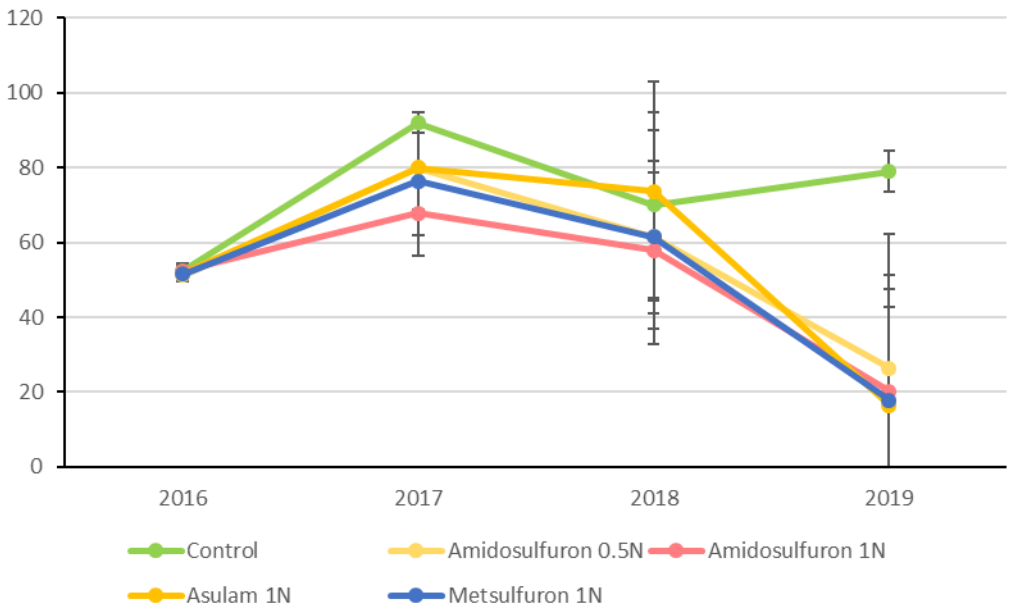


Figure 163. Mean (± standard deviation) litter cover (%) 2016-2019 at Fawdon Farm, Northumberland, split by chemical treatments

```
            Df Sum Sq Mean Sq F value  Pr(>F)
Chemical     4  15160    3790   4.614 0.00548 **
Residuals   28  23001     821

Significant pairwise comparisons:
                           diff         lwr       upr     p adj
Control-Amido 0.5N     51.857143    2.962559 100.75173 0.0335271
Control-Amido 1N       58.714286    9.819702 107.60887 0.0126410
Control-Asulam 1N      63.285714   14.391131 112.18030 0.0063971
Metsulf 1N-Control    -61.142857 -110.037441 -12.24827 0.0088260
```

Table 77. ANOVA & Tukey range test on litter cover 2019 (%) in chemical treatment plots at Fawdon Farm, Northumberland

```
        Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 15.04, df = 1, p-value =
0.0001052
```

Table 78. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) Ewe Hill (grazing, no cattle foddering) vs. Wether Hill grazing & winter cattle foddering) at Ingram Farm, Northumberland.

```
        Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 16.192, df = 3, p-value =
0.001036

Dunn (1964) Kruskal-Wallis multiple comparison
  p-values adjusted with the Benjamini-Hochberg method.

            Comparison           Z      P.unadj        P.adj
1       Bash - Control   2.3853627 1.706229e-02 0.0511868724
2           Bash - Cut  -1.6117315 1.070204e-01 0.1284244446
3        Control - Cut  -3.9970942 6.412478e-05 0.0003847487
4    Bash - Double-bash  0.3610279 7.180786e-01 0.7180786161
5 Control - Double-bash -2.0243348 4.293571e-02 0.0858714268
6     Cut - Double-bash  1.9727594 4.852298e-02 0.0727844697


       Group Letter MonoLetter
1       Bash     ab         ab
2    Control      a          a
3        Cut      b          b
4 Double-bash     ab         ab
```

Table 79. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) Ewe Hill (grazing, no cattle foddering) at Ingram Farm, Northumberland.

```
        Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 6.6722, df = 2, p-value =
0.03558

Dunn (1964) Kruskal-Wallis multiple comparison
  p-values adjusted with the Benjamini-Hochberg method.

      Comparison          Z    P.unadj      P.adj
1 Bash - Control 0.06996463 0.94422181 0.94422181
2     Bash - Cut 2.27115945 0.02313733 0.06941198
3  Control - Cut 2.20119482 0.02772223 0.04158335

    Group Letter MonoLetter
1    Bash     ab         ab
2 Control      a          a
3     Cut      b          b
```

Table 80. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) Wether Hill (grazing & winter cattle foddering) at Ingram Farm, Northumberland.

```
Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 29.368, df = 4, p-value =
6.58e-06

Dunn (1964) Kruskal-Wallis multiple comparison
  p-values adjusted with the Benjamini-Hochberg method.

             Comparison            Z      P.unadj        P.adj
1        Bash - Control   0.35906580 7.195459e-01 7.994954e-01
2            Bash - Cut  -2.49568506 1.257142e-02 2.514283e-02
3         Control - Cut  -2.85475086 4.307060e-03 1.435687e-02
4     Bash - Double-bash -4.23057724 2.330924e-05 1.165462e-04
5  Control - Double-bash -4.58964304 4.440047e-06 4.440047e-05
6      Cut - Double-bash -1.73489218 8.275990e-02 1.034499e-01
7           Bash - Lime  -2.43169313 1.502843e-02 2.504739e-02
8         Control - Lime  -2.79075893 5.258462e-03 1.314616e-02
9             Cut - Lime   0.06399192 9.489767e-01 9.489767e-01
10    Doublebash - Lime   1.79888410 7.203702e-02 1.029100e-01
```

Table 81. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) for physical/liming treatments, Challacombe Farm, Devon.

```
        Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 6.5475, df = 4, p-value =
0.1618
```

Table 82. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) for chemical treatments, Challacombe Farm, Devon.

```
        Kruskal-Wallis rank sum test

data:  Displacement by Treatment
Kruskal-Wallis chi-squared = 3.1977, df = 4, p-value =
0.5253
```

Table 83. Kruskal Wallis test & Dunn's post-hoc test of cylinder displacement scores (1-14) for chemical treatments, Fawdon Farm, Northumberland.

```
Pearson's Chi-squared test

X-squared = 62.222, df = 3,
p-value = 1.969e-13

Post-hoc pairwise chi-square tests

             Comparison  p.Chisq   p.adj.Chisq
1            Cut : Bash 3.68e-03 1    4.42e-03
2     Cut : Double-bash 1.37e-05 2    2.74e-05
3         Cut : Control 2.37e-03 3    3.56e-03
4    Bash : Double-bash 7.01e-02 4    7.01e-02
5        Bash : Control 4.76e-09 5    1.43e-08
6 Double bash : Control 5.06e-12 6    3.04e-11
```

Table 84. Pearson's Chi-square test with post-hoc pairwise testing of proportion of damaged cylinders in 2019 by treatment (excluding liming). Sample is aggregation of Ingram & Challacombe Farm physical treatment data