Defoliation of Winter Oilseed Rape for Cabbage Stem Flea Beetle Management 19/20

Final report

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Image from field lab: Oilseed rape grazing © C. Eglington

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Summary

The control of cabbage stem flea beetle larvae by defoliating winter oilseed rape in the winter was investigated at five sites in England. Host farmers defoliated using a topper or grazing with sheep. The timing, duration and severity of defoliation differed between sites. Assessments of larval numbers in March showed that defoliation significantly reduced larval populations at four sites, with larvae per plant reduced by an average of 68%. Larval reductions were higher in grazed crops (75%) than topped crops (46%). In general, defoliation resulted in yield losses, with an average 12% yield reduction at sites where robust yield comparisons were possible. Yield results were similar to the previous field lab (2018/19) but differed from other previous work and may have been due to poor weather conditions preventing crop recovery and high levels of late larval invasion. Despite yield losses, most host farmers would consider using the approach again under the right conditions (e.g. a drier winter), for management of a forward crop or for weed control.

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1 Field lab aims

The aim of this field lab was to investigate the use of defoliation (by grazing and topping) to control larvae of cabbage stem flea beetle (CSFB, *Psylliodes chrysocephala*). CSFB is one of the most important pests of winter oilseed rape (WOSR), with the larvae feeding within the petioles and stems during the winter. Controlling CSFB larvae is challenging because they are difficult to target (as they primarily live within the plant) and many are resistant to pyrethroid insecticides. This work was designed to build on knowledge and experience gained in a previous Innovative Farmer field lab on the same topic performed in 2018/2019. The previous field lab showed promise as significant reductions in larvae were found in the majority of sites, however yield was negatively impacted. It was unclear as to whether the yield reduction was due to adverse weather conditions in 2019, so the field lab was repeated in 2019/20.

This field lab brought together a network of farmers willing to defoliate their WOSR to control CSFB larvae. By testing the approach on several farms across the country, we hoped to demonstrate the practicality of this control method, further understand impact on yield and encourage its adoption more widely within IPM.

2 Background

CSFB adults migrate into WOSR in August and September, laying eggs after a short period. Egg hatch usually occurs from October, continuing throughout the winter while conditions remain conducive. Freshly hatched larvae bore into the petioles and remain there throughout the winter before moving into the stem as they mature in early spring. Larval feeding significantly reduces yield, with yield reductions generally increasing with increasing larval number per plant (Purvis, 1986; White & Cowlrick, 2017; White *et al.*, 2020).

Foliar pyrethroids are the only the products registered for use against CSFB, however CSFB resistant to pyrethroids have been present in the UK since at least 2014 (Højland *et al.*, 2015) and these are now widespread (Figure 1). Despite the reduced control that pyrethroids provide (due to resistance), pyrethroid usage against CSFB has increased to record levels (Garthwaite *et al.*, 2018). Even where CSFB remain susceptible to pyrethroids, targeting larvae is difficult as they spend much of their time protected within the plant petioles and stems.

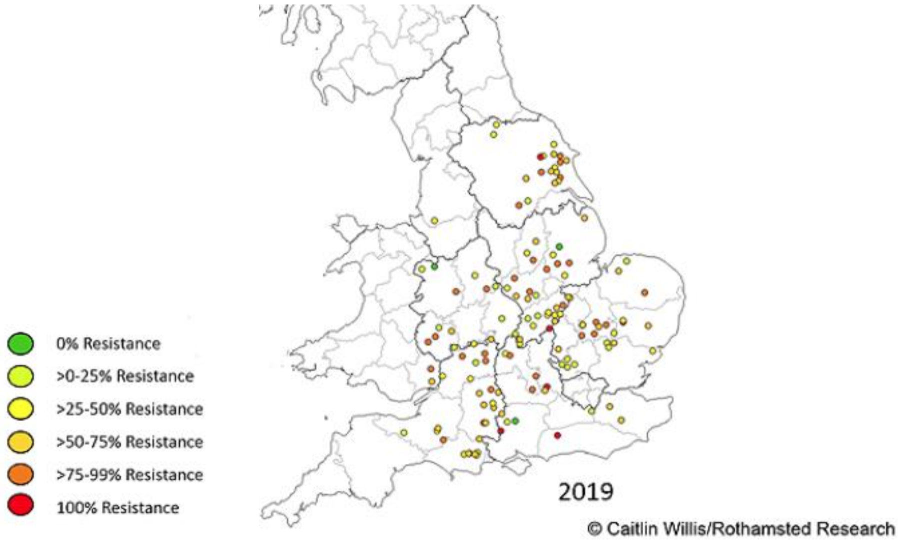

Figure 1 CSFB Pyrethroid resistance across England in 2019. Source: https://www.syngenta.co.uk/news/agronomy-issues/resistance-results-dictate-flea-beetle-actions

Previous work found that defoliation of OSR in the winter prior to stem elongation has minimal impact on yield (Spink, 1992; Lunn *et al.*, 2001; Sprague *et al.*, 2015; Ellis *et al.*, 2018). A randomised replicated plot trial was performed in 2016/17 that investigated whether defoliation could also be used to control CSFB larvae. Defoliation took place in December, January and March. Larval populations at the end of March were significantly (P<0.05) lower in defoliated than undefoliated plots (White *et al.*, 2018) (Figure 2). When taken to harvest, no significant difference in yield between the treatments was found.

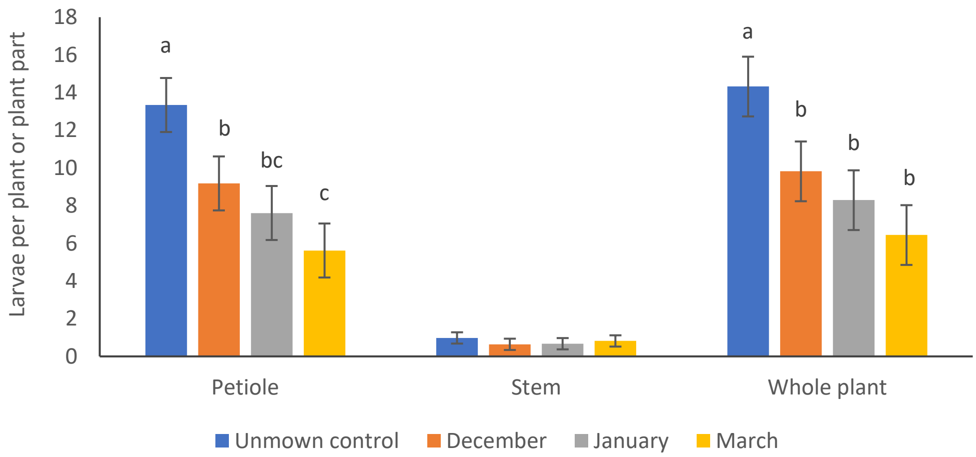

Figure 2 Mean larvae per whole plant and in the petioles and stems per plant in each defoliation treatment two weeks after the final defoliation treatment. Error bars indicate standard error of the difference between means. Letters indicate where significant differences between treatments were observed.

The defoliation method was tested further in 2018/2019, in a second randomised replicated plot trial and an Innovative Farmer field lab with host farmer participation at 12 sites across England. In the second plot trial the crop was defoliated in December, January and February. CSFB larval numbers were significantly reduced by up to 55% when the crop was defoliated in February (P<0.05). In contrast to the 2016/17 trial, defoliation significantly reduced yield by up to 24% (February defoliation) in comparison with the untreated control (Figure 3; White *et al.*, 2020). Differences in the yield results between the plot trials may have been due to poor weather conditions preventing crop recovery and high levels of late larval invasion in 2018/19.

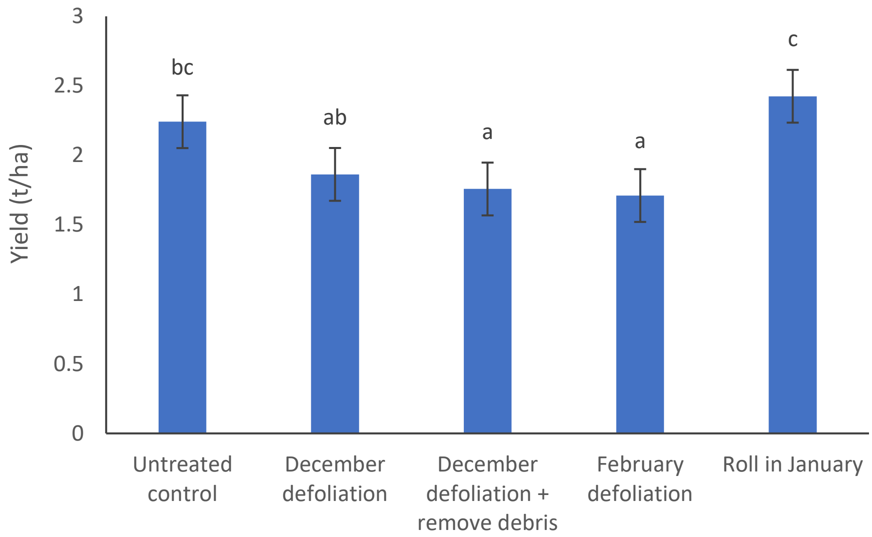

Figure 3. Mean yield of OSR (t/ha @91% DM) in July 2019 following defoliation and rolling treatments to control CSFB larvae. Letters indicate significant differences between treatments. Bars indicate the standard error of the difference between means.

In the 2018/19 field lab, host farmers defoliated using a topper or grazing with sheep at various times between late December and March. Assessments of larval numbers in March showed that defoliation significantly reduced larval populations at ten sites, with larvae per plant reduced by an average of 44% in grazed crops and 35% in topped crops (White & Kendall, 2019). In general, defoliation resulted in yield losses, with an average 14% yield reduction at sites where robust yield comparisons were possible. However, this field lab experienced similar growing conditions to those seen in the 2018/19 plot trial, which may have adversely affected crop recovery from defoliation. Conclusion of this work included that the defoliations ought to occur before February and ideally before January, and that early drilled crops may be better suited to defoliation.

3 Methodology and data collection

The field lab consisted of five farmers located in Yorkshire, Norfolk and Dorset. Farmers defoliated either using a topper (flail) or by grazing with sheep. As previous work had shown that defoliation after January is likely to result in yield loss, farmers were advised to make sure that any defoliation occurred before this time where possible. An overview of site details and defoliation dates are presented in Table 1 Overview of sites and treatments.

Table 1 Overview of sites and treatments

Site No.	Location	Drill date	Variety [target seed rate]	Treatments
1	Norfolk	11 August 2019	DSV Dariot [24 seed/m^2]	Grazed, Grazed with spray. (9-16 November)
2	Yorkshire	13 August 2019	V316OL [3.4 kg/ha]	Grazed (18 December -4 January)
3	Norfolk	14 August 2019	Elgar [63 seeds/m^2]	Topped (Mid-February)
4	Dorset	20 August 2019	Barbados [74 seeds/m^2]	1)Grazed early (27 December – 9 January) 2) Grazed late (9 - 21 January)
5	Norfolk	Unknown	Elgar [seed rate unknown]	Grazed: 26 September- 9 October, 10 - 24 October, 6- 16 November and 16- 25 November. Undefoliated crop in separate field

Host farmers were encouraged to use a trial design in which part of a field was defoliated and the remainder of the field was undefoliated, and to keep all other treatments post-defoliation the same. This would allow the best comparison of the impacts of the defoliation without needing to account for between-field variation and other treatment differences (e.g. fertiliser use). Host farmers were given guidance on how to set up the trial on their farm, including the minimum size of the defoliated area and how to choose the area to be defoliated to minimise any variation that could confound the results. At the time of finding participants, some farmers had already performed the defoliation but site layouts were suitable to participate. Site plans are presented in Appendix 1 (Figure 29 Figure 33). At site 4 the selected field was large enough to perform two defoliations with the aim to inform on the effect of grazing date on larval numbers (Appendix 1, Figure 32). At site 5, the whole field had already been defoliated over four dates before joining the field lab. For this site, comparative data was recorded from an undefoliated crop in a neighbouring field that had been drilled on the same day (Appendix 1, Figure 33). The impact of defoliation on green area index (GAI), CSFB larval populations and yield were assessed by ADAS. Yield data was collected by host farmers. After harvest, host farmers were asked a questionnaire covering their views on the field lab and the defoliation approach. On 26 November 2020, a project closing meeting occurred remotely (due to Covid-19 restrictions). Attendees included host farmers, researchers and funders. Results were presented by ADAS and experiences shared by each of the farmers involved, including a discussion on wider OSR management approaches.

Samplings and assessments

Each field was visited by ADAS staff in March to take GPS coordinates of the treatment areas (for use in analysing yield map data), take photographs for green leaf area index assessment (GAI) and to collect plants for larval assessments. At site 1 to 3, 30 plants were collected from each treatment area (defoliated and undefoliated). At site 4 and 5 where multiple grazed areas were included, 20 plants from each area were assessed. At each site, five plants were collected from four or six randomly selected locations within each area, with at least 10 m between each location and no closer than 50 m to the field edge and 3 m to the boundary of the treatment area. Plants were returned to an ADAS laboratory where all leaf petioles and stems were dissected with a sharp scalpel and CSFB larval numbers were recorded separately for the petioles and stems. Additionally, the larvae were classified into one of three size categories; small (< 3 mm), medium (3-5 mm) and large (> 5 mm), which equate approximately to larval instars 1, 2 and 3 respectively (Green, 2008). Comparison of larval population and GAI means within sites was analysed by ADAS staff using a t-test.

Yield map analysis

After harvest, host farmers were asked to provide yield map data from combines. Yield map data was analysed using a methodology and statistical package called Agronomics, which was specially designed by ADAS for determining yield differences within field trials. This methodology allows spatial variation to be accounted for so that treatment effects independent of this variation can be determined. Generating robust data on yield impacts is important to the wider adoption of this CSFB larval control method. Although yield map data was not available for all sites, participants provided observations on crops. The majority of farmers were able to provide yield map data.

Yield map data provided by the farmers was initially processed by excluding the following data from the analysis: headlands**,** areas of the field where underlying spatial variation would impact the fairness of the test**,** the ends of combine runs**,** combine runs which span the boundary between treatments, and combine runs which are anomalous, e.g. because the header is not full or yields were identified by the spatial model that were outside the expected range and as locally extreme.

Spatial models are fitted to the data to account for spatial variation across rows and along rows, and for the effect of the treatment. A modelled treatment effect on yield is calculated, which may not be the same as the difference between the average yields in each treatment. This is because the average yields may be biased by underlying variation, which is removed before calculating the modelled treatment effect. A standard error for the treatment effect allows calculation of statistical confidence limits and the probability that the treatment gave a higher yield than farm standard in the absence of other spatial variation.

4 Results

GAI Assessments

Green leaf area index (GAI) measurements were taken in March. Example photographs and corresponding mean GAI from each site are presented in Figure 4 toFigure 8. Details of the statistical output for GAI are presented in Table 2 (Appendix 2).

At site 1, the headland of the defoliated area was sprayed with the herbicide Fox in autumn for weed control. As this part of the field was treated differently it was sampled separately. However, it quickly became apparent that the spray negatively impacts the plant growth by March, with mean GAI in the grazed and sprayed crop only 0.36 in comparison to 0.64 in the area grazed but not treated with Fox. Therefore, only the defoliated area which was not sprayed is considered further in the results.

At all grazed sites with the exception of site 5, the grazed crop had significantly less GAI in March than the undefoliated crop ($P<0.001$). The reduction in GAI in grazed areas ranged from 34 to 84% (Sites 1 to 4). At site 5, all grazed areas had reduced GAI compared to the control field ($P<0.001$), however this difference was only statistically significant in the areas grazed between 10-24 October (72% reduction) and 16- 25 November (49% reduction) (Figure 8).

In the topped site (site 3), GAI was significantly reduced by 27% in the topped crop (P<0.001) compared to the undefoliated crop (Figure 6). This reduction in GAI was less than any of the grazed sites and suggests that topping was a less intensive form of defoliation than grazing.

Undefoliated (2.3 GAI)

Grazed 9 -16 November (0.64 GAI)

Figure 4 Site 1 (Norfolk) Mean GAI and representative photograph of plants in March

Undefoliated (2.51 GAI)

Grazed 18 December -4 January (0.6 GAI)

Figure 5 Site 2 (Yorkshire) Mean GAI and representative photograph of plants in March

Undefoliated (1.3 GAI) Topped Mid-February (0.93 GAI)

Figure 6 Site 3 (Norfolk) Mean GAI and representative photograph of plants in March

Undefoliated (2.3 GAI) Grazed 27 December - 9 January (0.78 GAI) Grazed 9 – 20 January (0.83 GAI)

Figure 7 Site 4 (Dorset) Mean GAI and representative photograph of plants in March

Undefoliated (2.4 GAI)

Grazed 26 September - 9 October (1.9 GAI)

Grazed 10 - 24 October (0.7 GAI)

Grazed 6 - 16 November (1.5 GAI)

Grazed 16 - 25 November (1.23 GAI)

Figure 8 Site 5 (Norfolk) Mean GAI and representative photograph of plants in March

From previous work, it was expected that early defoliated crops would have a higher GAI by March as they had longer to recover following defoliation. However, there is no trend in GAI reduction in comparison to defoliation date (

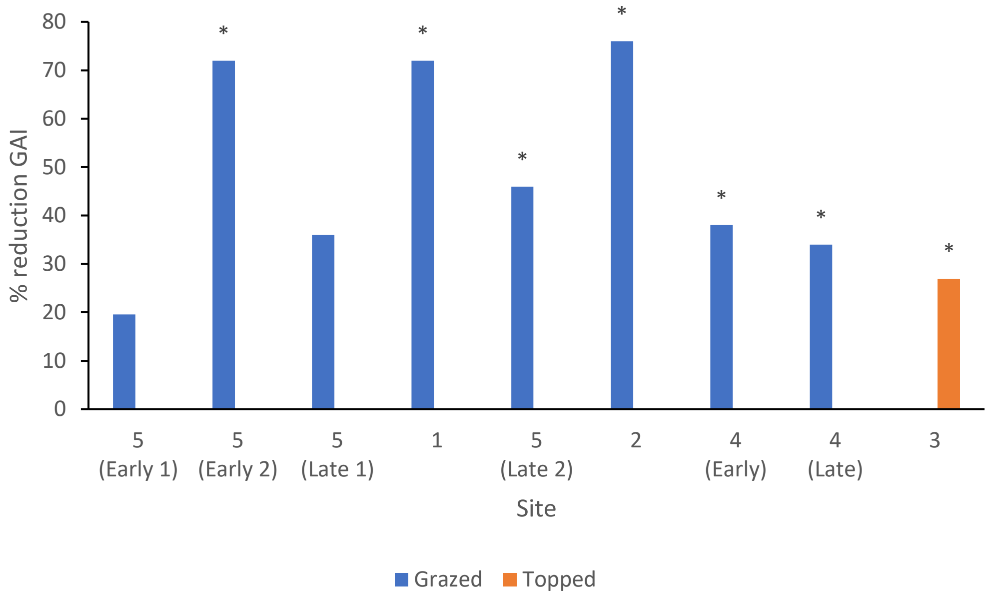

Figure 9), even at sites with multiple defoliated areas (site 4 and 5). This suggests that GAI in this trial was more dependent on intensity of grazing than defoliation date.

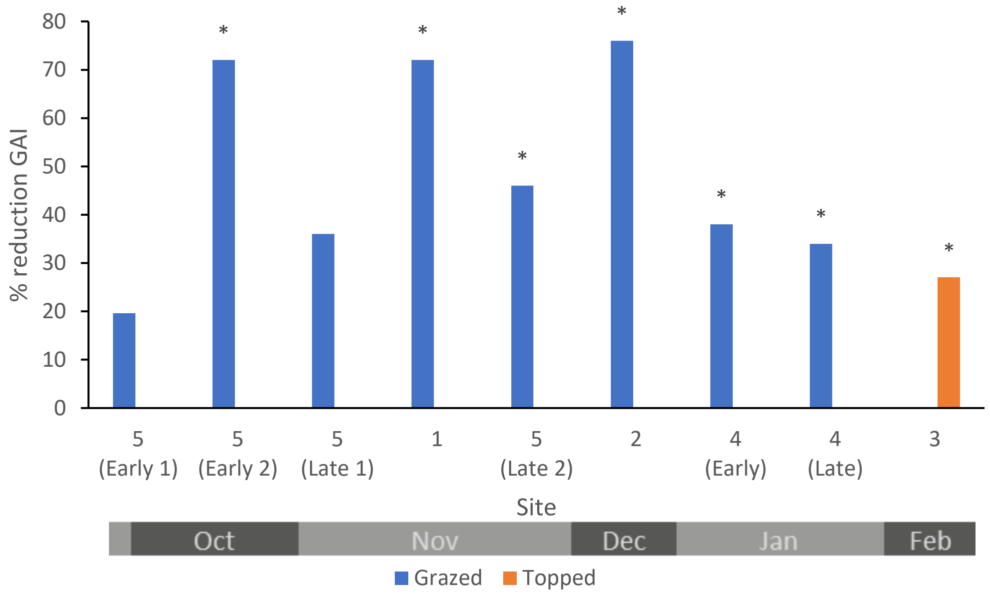

Figure 9 Reduction in GAI in defoliated crops in comparison to undefoliated crops. Sites ordered from earliest defoliated (left) to latest (right). Approximate month of defoliation shown in grey bar.
** shows statistically significant reduction in comparison to the undefoliated crop (P<0.001).*

Larvae

Numbers of CSFB larvae in the petioles, stems and the plant as a whole are shown in Figure 10 toFigure 14. Many more larvae were recovered from the leaf petioles than from the stems at all sites (e.g. at site 1, 82% of all larvae recorded were found in the petioles compared to 18% in the stems).

CSFB larval pressure varied between sites. The highest pressure was at site 1 (Norfolk) where 55 larvae/plant were found in the undefoliated crop (Figure 10). In contrast, only 3.7 larvae/plant were found in the undefoliated crop at site 2 (Yorkshire).

In four of the five sites (sites 1-4), there were significant reductions in the number of larvae within the petioles and the whole plants in the defoliated crop (P<0.001) compared to undefoliated crop. In grazed sites (1-3), larvae within the whole plant were reduced by 66 to 78% by defoliation (Figure 10 Figure 12). In the topped site, a 42% reduction in total larvae was found (Figure 13), which suggest topping was less effective at reducing larvae than grazing. At site 1 and 4 (both grazed), the number of larvae found within the stem in the defoliated crop was also significantly reduced by 24 to 70% (P<0.001). The number of larvae in the stems at site 2 and 3 were reduced by 12.5% and 31% respectively, but this was not statistically significant (P>0.05).

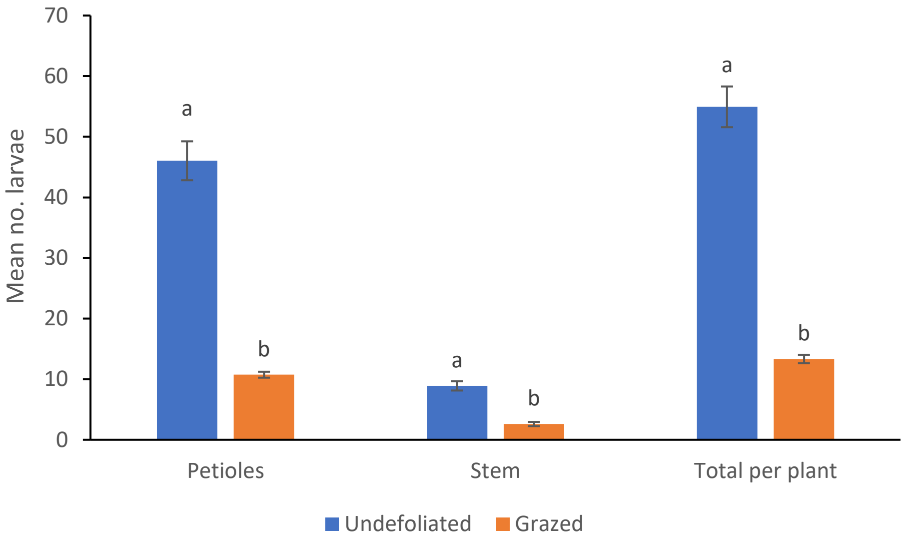

Figure 10 Site 1 Mean larvae in petioles, stems and total per plant in March in each defoliation treatment. Different letters show where significant differences between treatments were observed (P<0.001). Error bars show standard error of the mean.

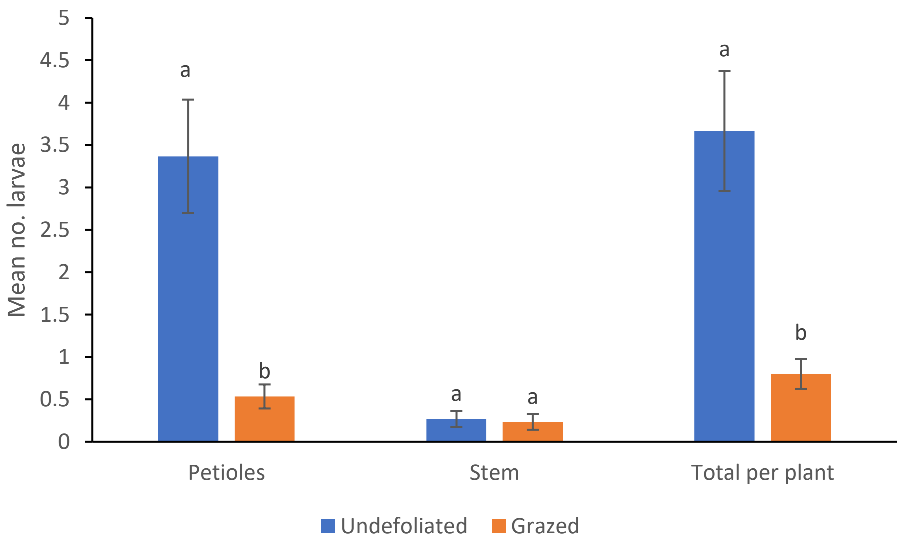

Figure 11 Site 2 Mean larvae in petioles, stems and total per plant in March in each defoliation treatment. Different letters show where significant differences between treatments were observed (P<0.001). Error bars show standard error of the mean.

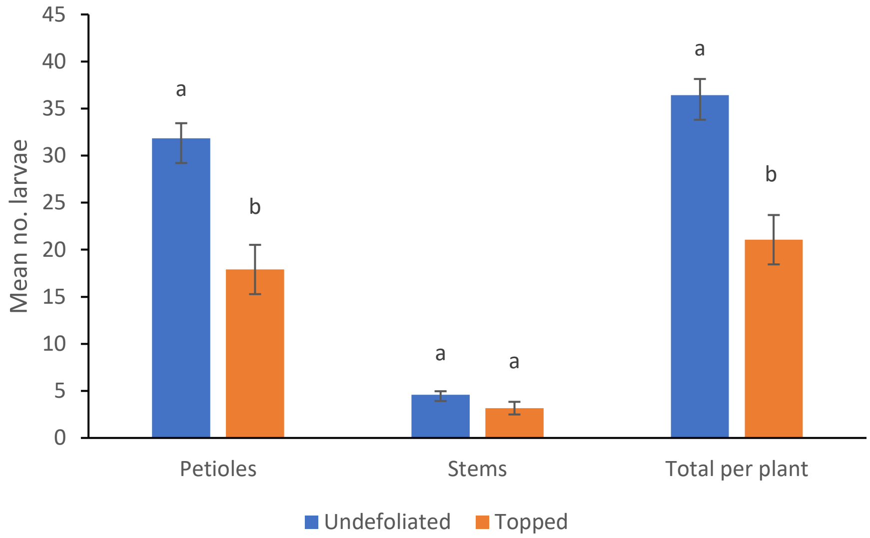

Figure 12 Site 3 Mean larvae in petioles, stems and total per plant in March in each defoliation treatment. Different letters show where significant differences between treatments were observed (P<0.001). Error bars show standard error of the mean.

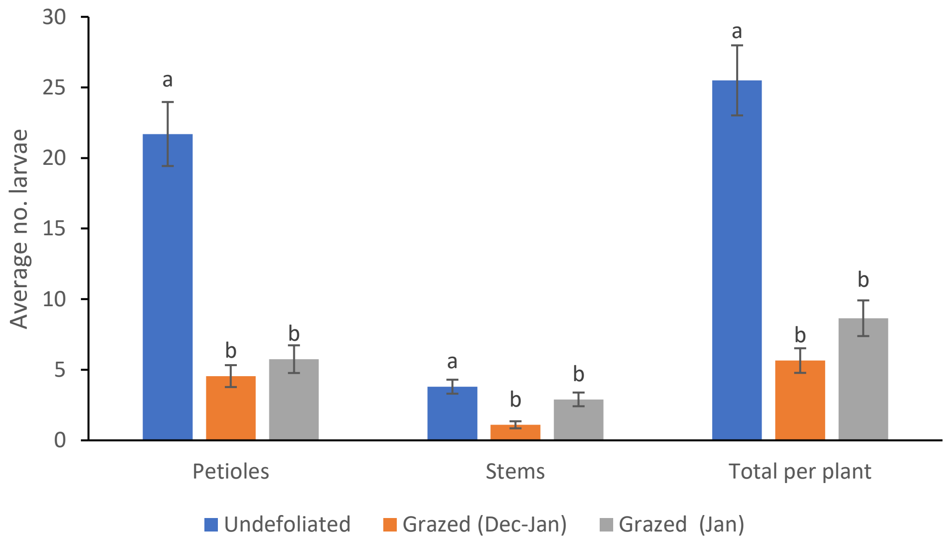

Figure 13 Site 4 Mean larvae in petioles, stems and total per plant in March in each defoliation treatment. Different letters show where significant differences between treatments were observed (P<0.001). Error bars show standard error of the mean.

In the remaining site (site 5), the response to defoliation was inconsistent (Figure 14). Grazed crops to the north of the defoliated field (grazed from 10 to 24 October and 16 to 25 November), showed an increase in number of larvae per plant (by 22 and 32% respectively) in comparison to the undefoliated field. These differences were not statically significant. However, a significant increase in the number of larvae was found in the stems in the latest grazing treatment (158%; 16 to 25 November) in comparison to the undefoliated field. In contrast, treatments in the southern half on the field (26 September to 9 October and 6 to 16 November) showed the number of larvae was reduced following defoliation by 27 and 24% respectively compared to the undefoliated field. No further statistically significant differences were found in comparison to the undefoliated area at this site. Details of the statistical output for larval numbers are presented in Table 3 (Appendix 2).

The lack of larval reduction at site 5 is likely to be because the undefoliated crop was located in a separate field, where CSFB larval pressure was possibly lower. As established in the previous field lab (2018/19), ensuring all treatments are within one field is the preferred design as CSFB pressure can vary between fields.

When comparing the graze dates within the defoliated field, based on observations in previous work we would have expected to find fewer larvae in the later grazed areas. This was not the case at site 5, and there was no clear trend between graze date and number of larvae found. This may be because all defoliations at site 5 were performed early (September to November) so there was little difference in larval invasion over this period. Alternatively, the CSFB pressure may have varied across the grazed field. There is a woodland on the northern side of the defoliated field which could have been a source of CSFB adults and so leading to higher numbers of CSFB larvae in the adjacent area of crop (Figure 33 in Appendix 1). In contrast, adjacent to the southern half of the field is a main road, which can be considered an ecological desert and so may have resulted in fewer adult CSFB invading the field from this side and lower CSFB larval numbers in the southern half of the field.

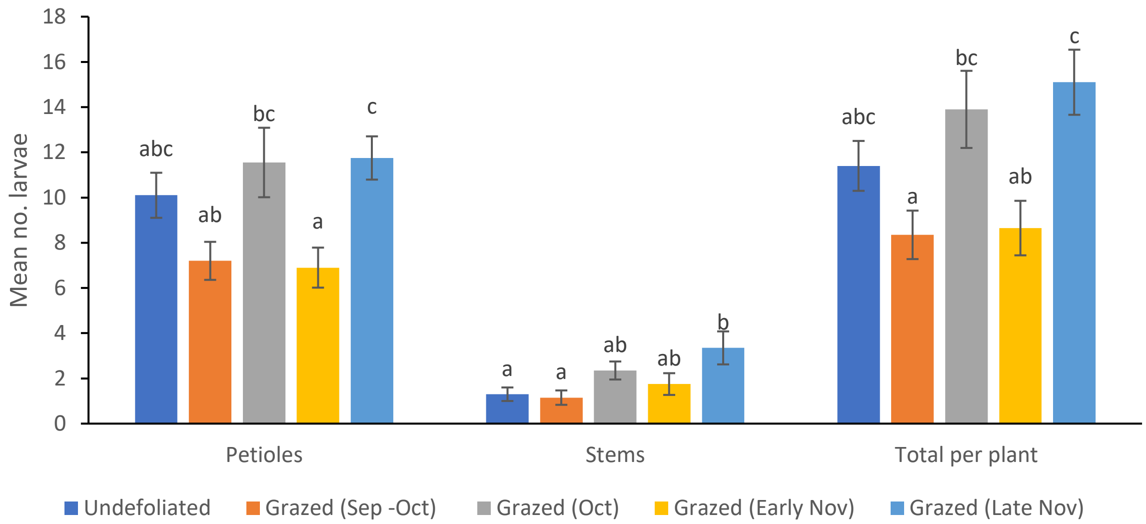

Figure 14 Site 5 Mean larvae in petioles, stems and total per plant in March in each defoliation treatment. Different letters show where significant differences between treatments were observed (petioles and whole plant P<0.001, stem P =0.009). Error bars show standard error of the mean.

There was no clear trend in reduction in larvae in comparison to date of defoliation (Figure 15) which suggests reduction in larvae was driven by intensity of defoliation and type of defoliation.

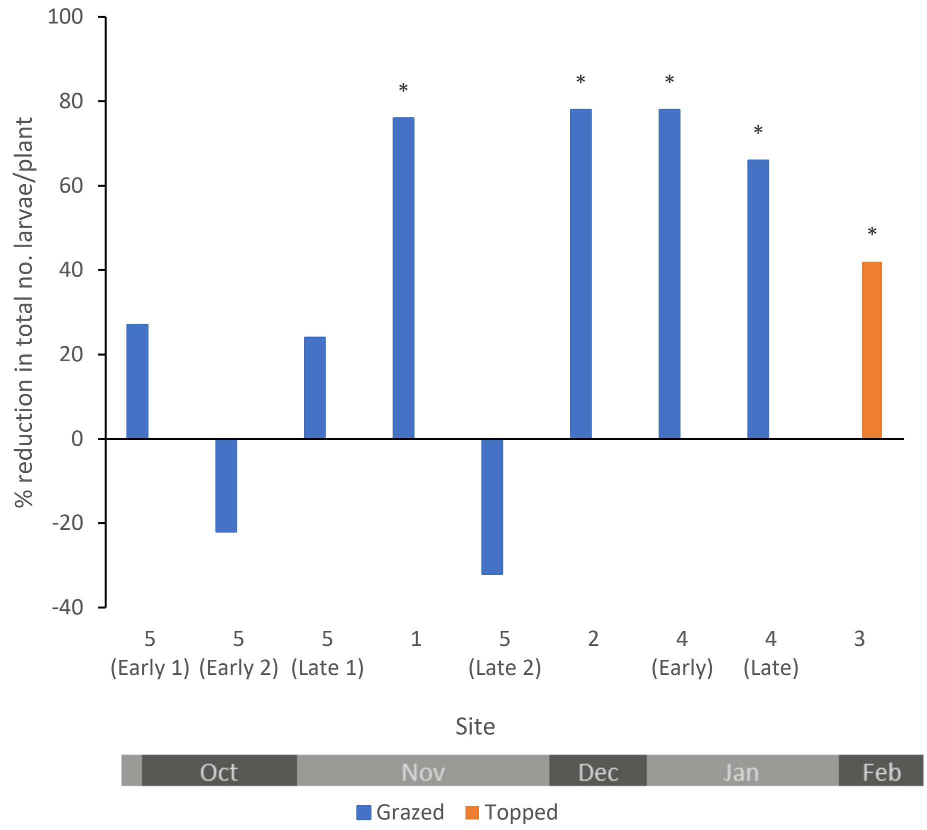

*Figure 15 Mean reduction in number of larvae in whole plant at all sites. Sites ordered from earliest defoliated (left) to latest (right). Approximate month of defoliation shown in grey bar. * shows significant difference between defoliated and undefoliated crop. Note: at site 5 the undefoliated crop was in separate field.*

Larval size was also recorded in March at each site and is presented in Figure 16Figure 20. At sites 1, 2, and 4, grazing lead to clear reductions in the proportion of large larvae present. This suggests that the majority of the larvae removed by grazing were ingested or trampled by sheep and did not reinvade the plants. Instead, these were replaced by larvae that hatched and invaded plants after the defoliation, which accounts for the higher proportion of small and medium larvae at these grazed sites. In contrast at the topped site (3), size proportions were similar in the topped area compared to the undefoliated crop (Figure 18). This may be because more larvae are able to survive topping and reinvade plants than for grazing. Also, this was the last site to be defoliated (February), leaving less time for invasion of freshly hatched larvae than at other sites, which would result in these having a smaller dilution effect on the population structure at this site.

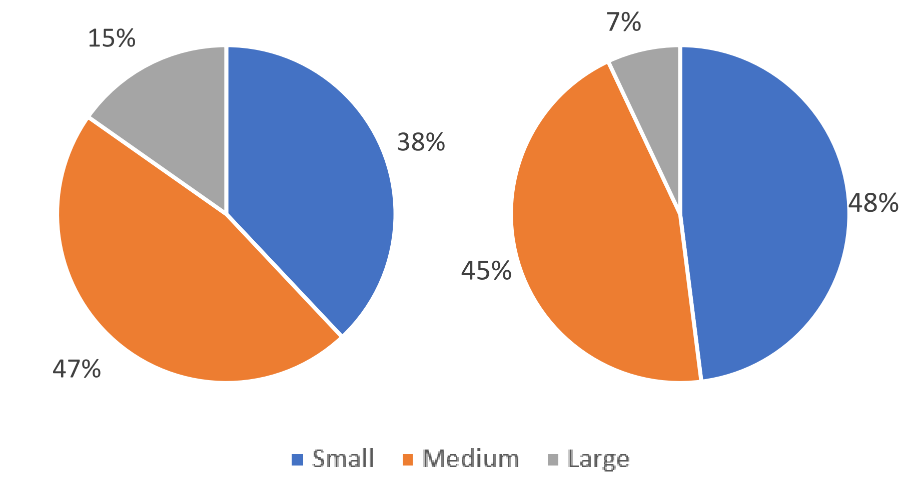

Figure 16 Site 1 Proportion of larvae per plant per size category in the undefoliated (left) and defoliated crop (right).

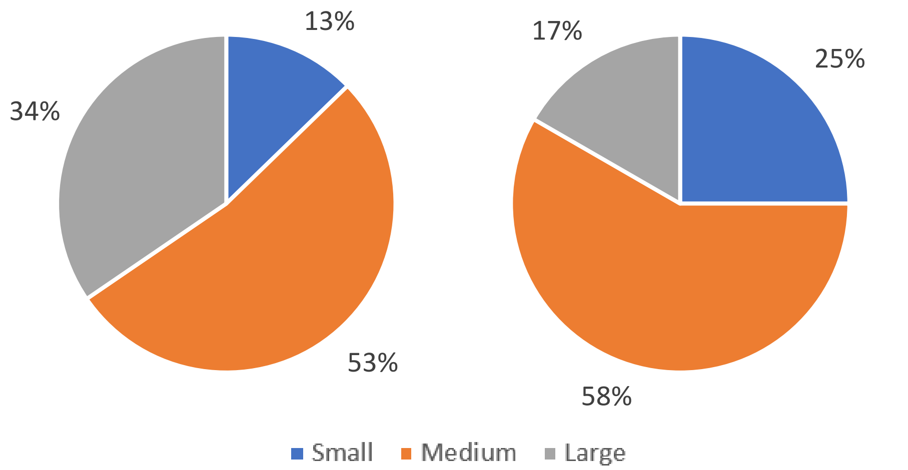

Figure 17 Site 2 Proportion of larvae per plant per size category in the undefoliated (left) and defoliated crop (right).

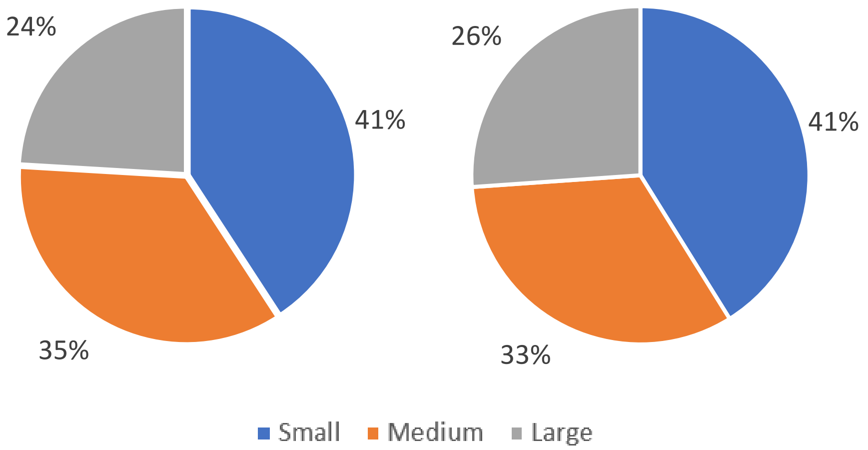

Figure 18 Site 3 Proportion of larvae per plant per size category in the undefoliated (left) and defoliated crop (right).

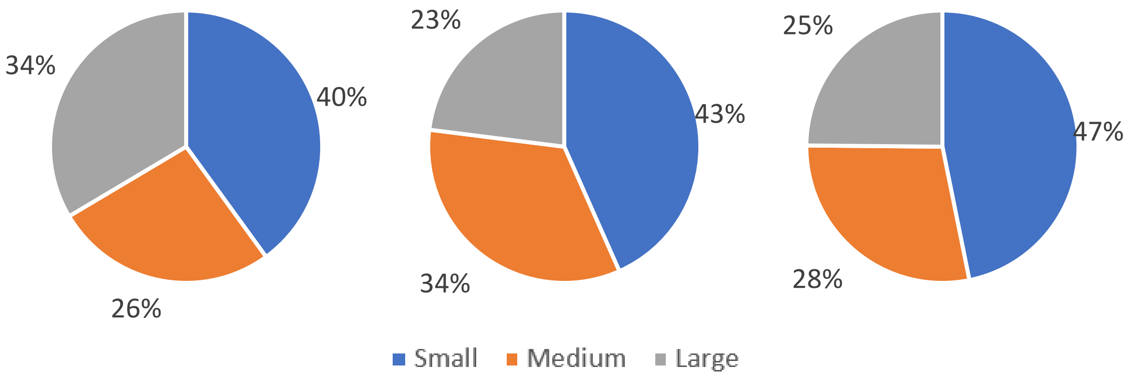

Figure 19 Site 4 Proportion of larvae per plant per size category in the undefoliated (left) and early defoliated crop (middle; 27 December to 9 January) and late defoliated crop (right; 9 to 21 January).

At site 5, the proportions of different larval sizes were similar in defoliated areas in comparison to the undefoliated field (Figure 20), which is inconsistent with the other grazed sites within this project and is probably because the undefoliated field was located in a separate field and so subject to differences in CSFB pressure. Furthermore, within the defoliated field there was no clear trend between defoliation date and proportion of larval sizes. This may be because all defoliations at site 5 were performed early (September to November) so that there was little difference in larval invasion over this period and similar levels of subsequent late larval invasion between the areas.

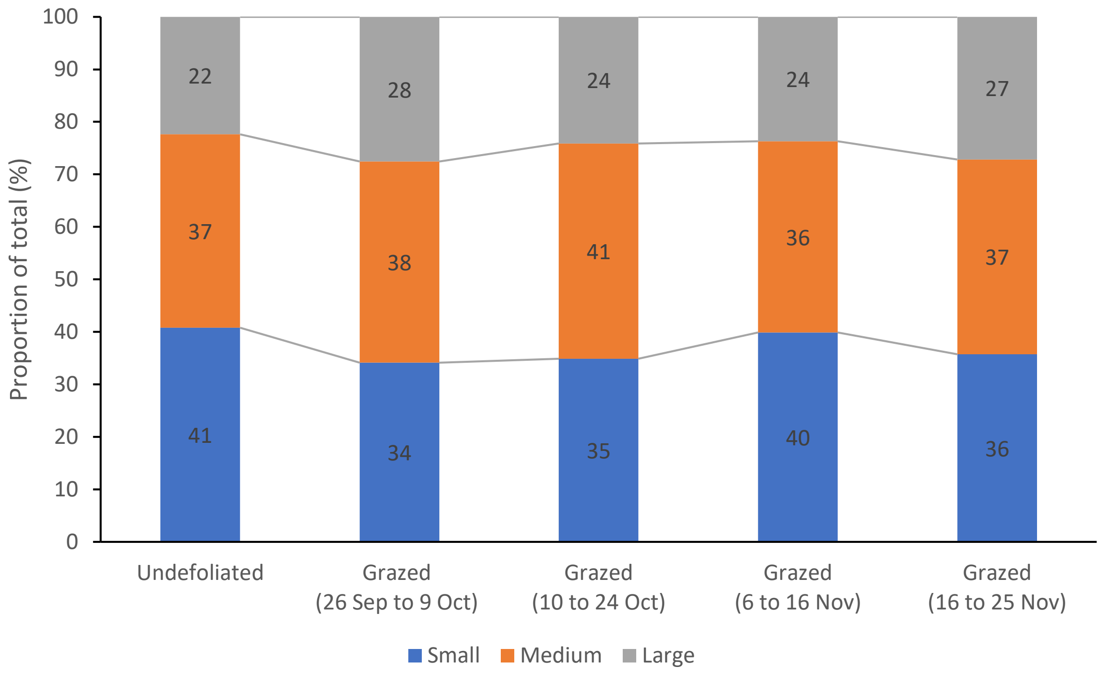

Figure 20 Site 5 Proportion of larvae per size category per plant for undefoliated and grazed crops.

Yield

There was significant yield reduction in all three sites where yield data was available (site 1, 2 and 4; P<0.05). Yield loss as determined using Agronomics analysis ranged from 0.284 to 0.853 t/ha which is equivalent to 6.3 to 20.8% of the mean undefoliated yield (Figure 21**Error! Reference source not found.**). Unexpectedly, the sites where defoliation was performed earliest had the largest yield loss, despite having more time to recover from defoliation. Yield loss is more likely to be determined by intensity of grazing, than drill date in this project. Further details regarding yield at each site are described below.

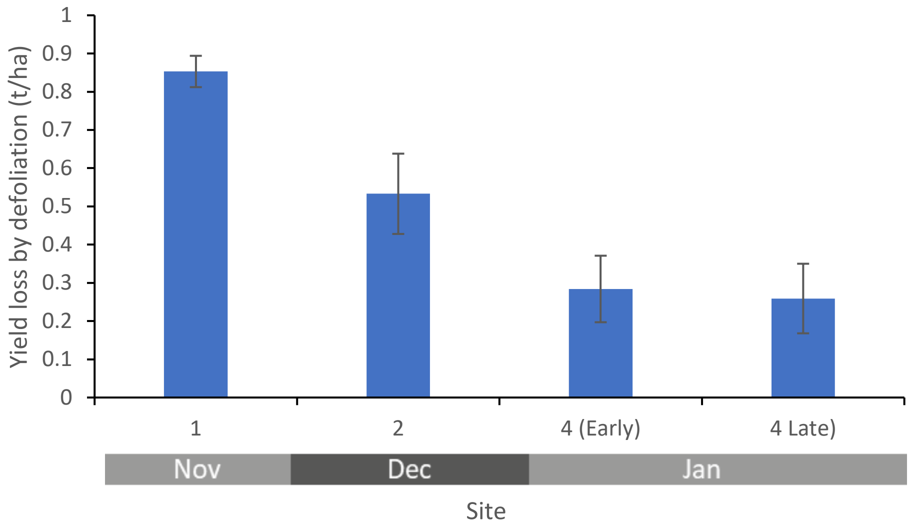

Figure 21 Yield loss due to defoliation for site 1, 2 and 4 as predicted by Agronomics. Error bars show 95% confidence intervals. Sites ordered from earliest defoliated (left) to latest (right). Approximate month of defoliation shown in grey bar.

At site 1, the yield of the defoliated crop was 21% lower than the undefoliated crop. However, the position of the defoliated area (which was chosen by the host farmer prior to joining the project) may have had an influence. The northern area of the field surrounding the defoliated area had slightly lower yields than the south (Figure 22), suggesting that this area of the field had lower yield potential. Additionally, the northern side of the field had higher weed pressure (e.g. charlock), which is the reason the host farmer defoliated this area as he had noticed that in the 2018/19 field lab sheep had eaten the charlock first. These factors may have contributed to the reduced yields in the defoliated area, however they are unlikely to account for the entire yield reduction. Defoliation would have had an important impact on the yield reduction.

Figure 22 Site 1 Yield map (t/ha). Defoliated area shown in red box, remainder of the field was undefoliated.

At site 2, the yield of the defoliated crop was 13% lower than the undefoliated crop (Figure 23). Some flooding was experienced in the eastern edge of the field in the defoliated crop, so this data was excluded to reduce variation and bias within the yield results. Additionally, due to the size of the field and number of data points, some data had to be excluded. To reduce bias, data closest to the field edges were excluded, and data closest to the boundary between the treatments retained.

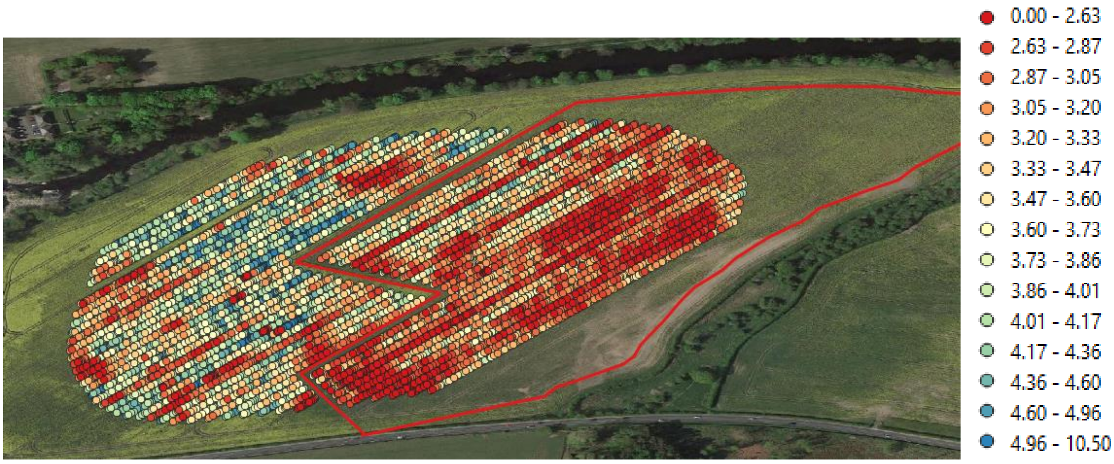

Figure 23 Site 2 Yield map (t/ha). Defoliated area shown in red box, remainder of the field is undefoliated. Area of flooding on eastern boundary of the field excluded from the results as shown.

At site 4, the yields in the early (27 December and 9 January) and late defoliated crop (9 and 21 January) were 6.9 and 6.3% lower than the undefoliated crop respectively (Figure 24). Yield reductions were similar in both grazed crops which is likely to be due to similar defoliation dates, as all grazing was completed within approximately a month.

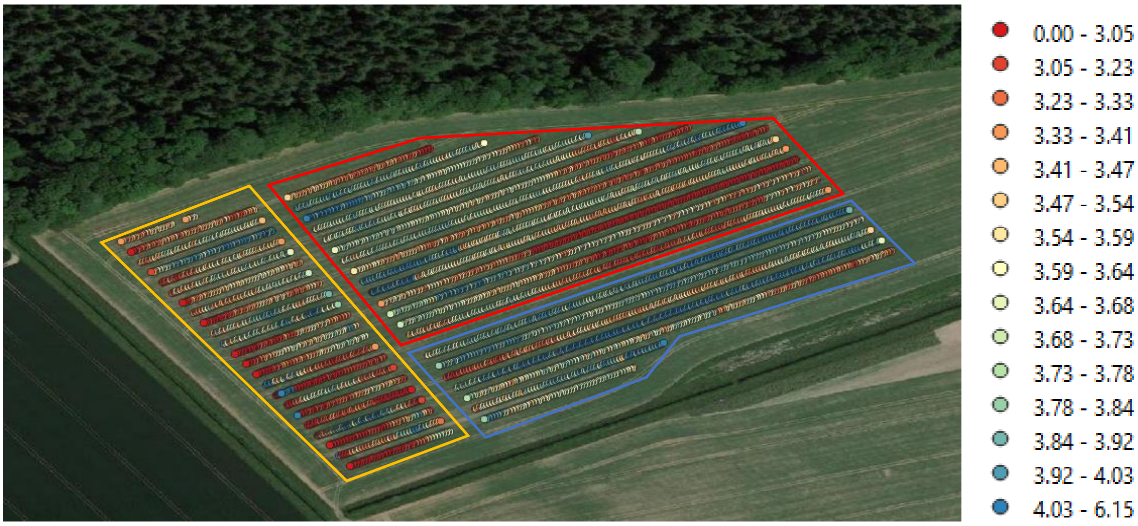

Figure 24 Site 4 Yield map (t/ha). The early defoliated area is shown in a yellow box, late defoliated area in a red box, and undefoliated area in a blue box.

No yield map data was available at site 3 (topped) or site 5 (grazed) due to difficulties recording or transferring the yield data. Unfortunately, yield of the defoliated and undefoliated areas were also not measured separately by weighbridge at these sites. However, the host farmer at site 3 observed that yields were poor in both treatments and did not notice any additional loss by defoliation.

Participant views on defoliation

Four of the participating host farmers provided their views on defoliation. The participants found performing defoliation practical as sheep and equipment were available, but that grazing in particular was time consuming and labour intensive as fencing needed to be moved frequently to prevent overgrazing. It was noted by one participant that it would probably be best to move sheep frequently (every 1-3 days) and back fence them to prevent them returning to already grazed areas. For the majority of grazed sites, erecting and moving fences was considered the main cost (excluding yield reduction), although at some sites sheep would have been treated similarly in turnip crops anyway, so no additional costs were associated. One participant observed that the sheep were initially reluctant to feed on the OSR but soon developed a taste for it. An unexpected benefit at site 4 was that the lambs used for grazing fattened much more quickly than in previous years, which had financial benefits as other livestock were fed with the unused turnip crops and were able to stay outdoors for longer, in turn reducing the costs of bedding. Additionally, the use of home saved seed at site 4 was considered to further reduce the cost and risks of defoliation. At the topped site (3) the associated costs of defoliation were thought to be £5/ha to perform the topping (diesel and labour). Two of the participants found additional weed control (e.g. charlock, grasses, volunteer barley) to be a further benefit of grazing.

The downsides of defoliation, as identified by participants, were increased compaction from grazing where conditions were too wet and (at site 2) more stem canker was found in the grazed crop, which resulted in increased stem lodging. The latter is in contrast to results from the 2018/19 plot trial (White *et al*., 2020) where defoliation was seen to reduce stem canker although this was not formally measured.

Two of the participants stated that defoliation could be a useful crop management measure for early sown, forward crops. One participating farmer noted that he had seen no yield loss when he defoliated by grazing in 2018/19. In that year he had moved the sheep on every two days but moved them on less frequently in this field lab, which resulted in overgrazing. In fact, all participants that grazed thought they had overgrazed in this trial, which resulted in increased crop damage from both feeding and trampling, and if they used grazing again would do so less intensively to limit yield impact. An example of the extent of grazing are shown in Figure 25. One of the farmers that grazed stated that he intended to do so again in 2020/21, targeting an early drilled crop by introducing sheep early, primarily for charlock control. Two more participants that grazed crops would consider using defoliation again in the right conditions (e.g. by targeting forward crops and by reducing the intensity of the grazing). The participant that defoliated by topping does not intend to perform defoliation in future due to the lack of yield benefit.

Other observations were that two participants were committed to using no insecticides as they felt these were providing no benefit and would be harming beneficial insects that may be providing control of CSFB and other pests. One participant also felt that CSFB larvae were having little impact on the crop at his site. This was despite his undefoliated crop having 55 larvae per plant. This is discussed further below.

Figure 25 Site 1 (Norfolk) showing the intensity of grazing (centre and right) in comparison to undefoliated area (left) one month after grazing. Photograph provided by Chris Eglington.

Participant feedback on field lab

Participating farmers in general found the trial useful and interesting, and some expressed an interest in participating in future trials. Benefits included additional crop monitoring, access to advice and the ability to discuss topics of interest. It was noted that it would have been good to meet face to face to discuss results, which unfortunately was not possible due to Covid-19 restrictions. However, this would be preferred for future field lab trials.

5 Discussion

In this field lab, defoliation was shown to be a very effective control for CSFB larvae at four sites. On average larvae were reduced by 75% in grazed crops and 46% in topped crops. This is in agreement with the previous field lab (White & Kendall, 2019) and other defoliation work (White *et al.*, 2018; White *et al.*, 2020). In both the 2018/19 and 2019/20 trials, grazing was found to be more effective than topping at reducing the number of larvae. In this years' trials, GAI taken in March showed that topped plants had a smaller reduction in GAI than grazed plants, suggesting that topping is a less rigorous form of defoliation than grazing. The reduced level of plant tissue removed by topping compared to grazing would result in greater numbers of larvae remaining within the plant. There is also likely to be greater levels of larval mortality in grazed situations because larvae would not survive being ingested by sheep and because sheep would trample larvae in plant debris on the ground. It should be noted that grazing was generally thought to be too intensive in this work and so it is likely that were less intensive grazing used then reductions in larval numbers would be lower.

In the 2018/19 field lab, there was a weak trend that later defoliations in general gave better larval control. In contrast, no trends between larval reduction and defoliation date were observed this year. The reason for this difference is unclear but it may be due to differences in the timing of late egg hatch and larval invasion between the years, both of which are strongly influenced by weather (White *et al.*, 2020). In the 2018/19 trial, defoliated crops still had 10 to 16 larvae per plant by the final assessment in March, suggesting high levels of larval invasions after defoliation. Whereas in the 2019/2020 field lab, average numbers of larvae in grazed sites were lower and ranged from 0.8 to 13 larvae per plant. In 2019/20, late larval hatch may have been hindered by wet winter conditions, which may have damaged or washed away eggs (Figure 26). This is supported by very low larval pressure at site 2 (3.7 larvae/plant in undefoliated crop) which experienced severe waterlogging and some flooding. As such, in 2019/20 it is thought that level of larval control was primarily influenced by intensity (and type) of defoliation and weather as opposed to drill date.

In the three sites able to provide yield data for analysis, a yield reduction of 6.3 to 21% was observed. This is comparable to the previous field lab in 2018/2019 where an average yield loss in defoliated crops was 14% compared to undefoliated crops. The trend for yield reductions in defoliated crops in the two field labs differs from previous UK trial work, which showed that defoliation before March, and certainly before stem elongation, had no significant impact on yield (Spink, 1992; Lunn *et al.*, 2001; Ellis *et al.*, 2018; White *et al.*, 2018). The poor yield results in the 2018/19 were in part attributed to poor weather conditions. Crops in 2019/20 similarly faced challenging growing conditions, with dry establishment conditions followed by a very wet autumn and winter, which can limit root development and establishment, especially if the ground becomes waterlogged as experienced at site 2 in Yorkshire. This was then followed by a dry spring (Figure 26), which is likely to have limited nutrient uptake and reduced the ability of defoliated crops to produce additional branches to compensate for the defoliation. For example, increased rates of nitrogen were applied to the defoliated area at site 1 to stimulate recovery, however a yield reduction of 21% was still found.

It is estimated that the national average WOSR yield in 2019/20 was 0.8 t/ha (23%) less than the 2016/17-2018/19 average, and the worst recorded since 2001 (Figure 27). Usually yield is not well associated with total crop biomass, however total plant biomass was strongly correlated to yield (91%) in 2020 (P Berry, unpublished data). This suggests total crop biomass was generally sub-optimal due to dry spring conditions even in undefoliated crops (P Berry, Pers. comm.). As a result, in the 2019/20 trial, defoliated plants would have been more disadvantaged than in a more typical year.

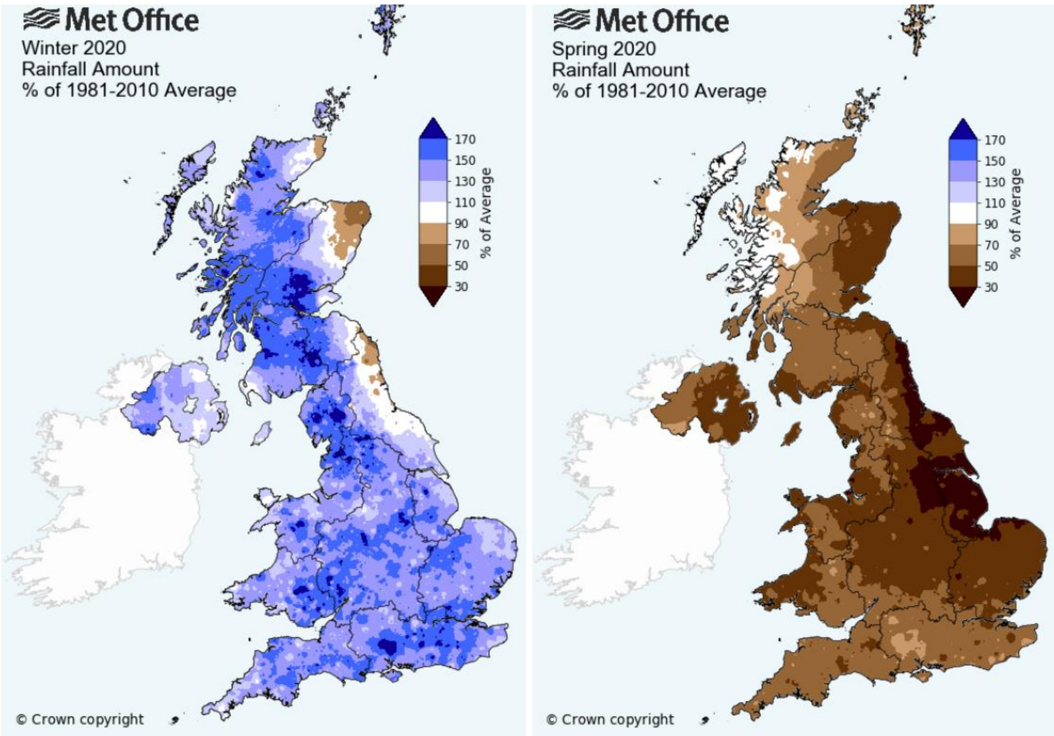

Figure 26 Rainfall 1981 - 2010 anomaly maps for winter 2019/20 (December to February; left) and spring 2020 (March to May; right). Taken from https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-actual-and-anomaly-maps.

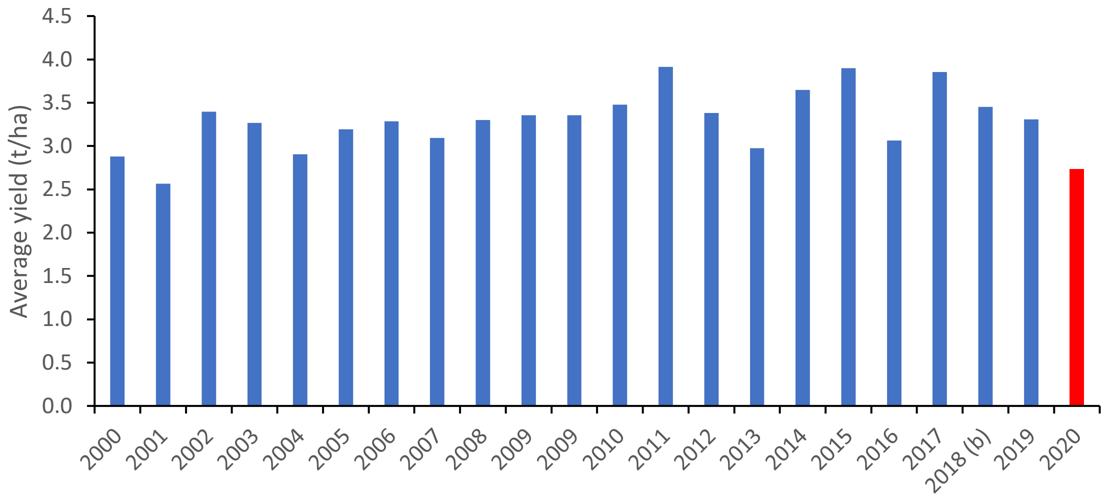

Figure 27 Average OSR yield (t/ha) in UK from 2000 to 2020. (DEFRA, 2020).

Poor yields in response to defoliations in the 2018/19 field lab were also attributed to late defoliation timings, as these gave crops limited time to recover from defoliation. An aim of the 2019/20 field lab was to investigate whether improved outcomes could be achieved by defoliating earlier, however results show that earlier defoliations did not produce reduced yield impacts. This may also be due to the influence of weather, with high autumn rainfall likely to have limited root development, which would limit crop recovery. In 2019/20, it is highly likely that the impact on yield was also influenced by the intensity of defoliation, as sites with the highest reduction in GAI by March also had the highest yield reduction.

The impact of defoliation on the timing of harvest, and the subsequent effect on the yield comparisons between the defoliated and undefoliated areas, should also be noted. Throughout the trial, plants in grazed areas were smaller and developmentally behind the undefoliated crop. Three of the participating farmers confirmed that flowering was delayed (by 10 days or more) in the defoliated crop compared to the undefoliated crop (Figure 28). In some cases a compromise had to be made as to when best to harvest the crop, because to allow for yield comparisons both areas had to be harvested on the same day despite the differences in development. At some sites this resulted in harvest occurring before the grazed area was fully ripe, which could have further contributed to poor yield in the grazed areas. No differences in development were observed by the farmer at the topped site.

Figure 28 Site 4 (Dorset) showing the difference in flowering between undefoliated (left) and defoliated (right). Arial photograph of site 4 on 24th June showing difference in ripening between the defoliated (left) and undefoliated crop (right). Photographs provided by George Hosford.

At site 2, an increase in stem canker and lodging was found in the defoliated crop, which will have further reduced yield in comparison to the undefoliated crop. This is in contrast to previous defoliation work, which found defoliation reduced stem canker (White *et al.*, 2020). The differences are likely due to a combination of weather and defoliation timing. Phoma, the causal agent of stem canker, is favoured by warm, wet conditions in summer and autumn. Such conditions prevailed in 2019 meaning that overall phoma pressure was higher in 2019/20 than 2018/19. Defoliation occurred earlier in the 2019/20 field lab than in the 2018/19 field lab. This is important in relationship to stem canker because if the leaves of plants infected before defoliation are removed by defoliation then stem canker may be reduced by breaking the connection between foliar infections and the stem. However, if infection occurs after defoliation then open wounds and smaller plant size may increase susceptibility to the disease. If considering defoliation, using a phoma resistant variety would reduce risks from stem canker. No difference in disease pressure was observed at the other sites in this field lab.

The impact of larvae on yield was questioned by a host farmer (site 1) who had participated in both the previous field lab and this one. In 2018/19 and 2019/20 the larval load in his undefoliated crop was 41 and 55 per plant respectively but achieved a yield of over 4 t/ha in both years. Previous work has found that yield loss increases with increasing larval load (Purvis, 1986; White & Cowlrick, 2017) but not in all cases (White *et al.*, 2020), indicating that some crops are better able to tolerate larval feeding than others. The basis of this tolerance is unknown but may be related to crop height, branching, stem width and /or spring vigour. It is interesting to note that the crop at site 1 was drilled early and at a relatively low seed rate (24 per m^2), and achieved a plant population at harvest of 13 plants per m^2. This resulted in large, tall plants, with high levels of secondary branching, and it is possible that these characteristics increased the ability of the crop to tolerate the high larval loads experienced.

Future of defoliation as a control method

As defoliation is a very effective form of controlling larvae, applying this method is likely to reduce the number of adult CSFB emerging from the crop. In turn, this may reduce CSFB pressure in following WOSR crops. Due to the high infestation rates found in crops currently and the limited control options available there is a concern that CSFB populations will continue to increase each year nationally. For example, the undefoliated crop at site 1 had an average of 55 larvae/plant and a plant population of 13 plants/m^2, meaning 7.2 million larvae/ha were produced in a single season with the potential to become adults and infest following crops. In contrast, defoliation reduced larval populations by 72% at this site, thereby reducing larval numbers to 2 million/ha and limiting potential pest pressures in following crops. Although it is unrealistic to assume all larvae will successfully develop into adults, this demonstrates the importance of utilising available controls to restrict pest return. Due to the mobile nature of the adult phase of the CSFB, adults may migrate from a neighbouring farm, therefore widespread adoption of defoliation could be most effective. However, there is still be value in individuals reducing local populations where possible. Certainly, consideration of CSFB management strategies that reduce overall populations of the pest need further consideration.

As results from this field lab and past research have shown variable impacts on yield from defoliation, growers should be aware that yield impacts are likely to be dependent on weather and late larval invasion pressure which cannot be predicted at the point of defoliation. As yield loss is a possibility, this method may be most applicable to mixed farming situations where costs can be saved through providing alternative fodder for sheep to reduce financial risk. All farmers who performed grazing commented that they had overgrazed. If farmers were to use this method in future, we would advise that growers monitor the defoliation stage carefully and be cautious with how vigorously they defoliate. The financial risk can be further reduced if home-saved seed is available. Defoliation can also be an opportunity to manage the size of forward, early drilled crops which are becoming increasingly common as farmers aim to avoid adult CSFB migration. Situations where this could be of further value is for specific weed control (e.g. charlock or cereal volunteers) and to generally provide long term CSFB population management.

6 Conclusions/Recommendations

Defoliation was successful at reducing larval pressure at the majority of sites (by up to 78%). Grazing was found to be a more effective method reducing larval load than topping. This is in part is because topping is a less intensive form of defoliation and larvae are more likely to survive in debris and so reinvade plants. Unfortunately, as in the 2018/19 trial, yield was reduced by defoliation at all sites that provided yield data. Although some past research has shown positive or no impact on yield, growers should be aware that yield reduction is likely to be dependent on weather and late larval invasion pressure, which cannot be predicted at the point of defoliation. As yield loss is a possibility, this method may be most applicable to mixed farming situations where costs can be saved through providing alternative fodder for sheep to reduce financial risk.

Advice for those interested in using this method would be to i) target crops that have experienced significant adult CSFB pressure to justify the defoliation, ii) target early drilled, non-backward crops in good soil as these tend to have higher larval populations (AHDB, 2018) and are likely to be more robust and with better rooting and so better able to tolerate the defoliation, iii) defoliate early (ideally before January and certainly before February or stem extension) to maximise the opportunity for the crop to recover, iv) carefully monitor crops whilst grazing and move sheep frequently (ever 1-3 days) to prevent over grazing and v) manage pigeon pressure by choosing a crop away from woodland and carefully use of deterrents.

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7 Appendices

Appendix 1: Site layouts

Figure 29 Site 1 field layout.

Figure 30 Site 2 field layout. Note: most eastern side of the field prone to flooding.

Figure 31 Site 3 field layout topped area shown in blue, remainder of the field was left undefoliated.

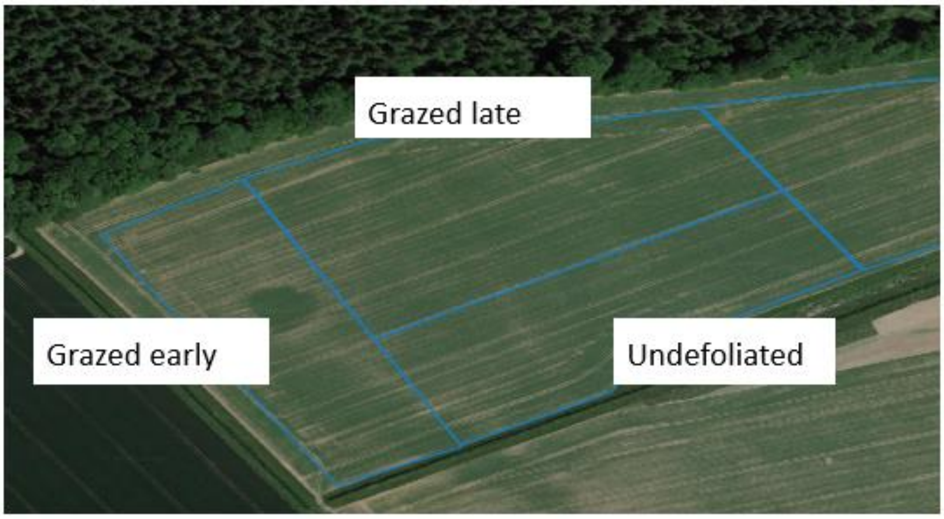

Figure 32 Site 4 field layout. Early site grazed from 27 Dec to 9 Jan 2019. Late site grazed from 9 to 20 Jan 2019.

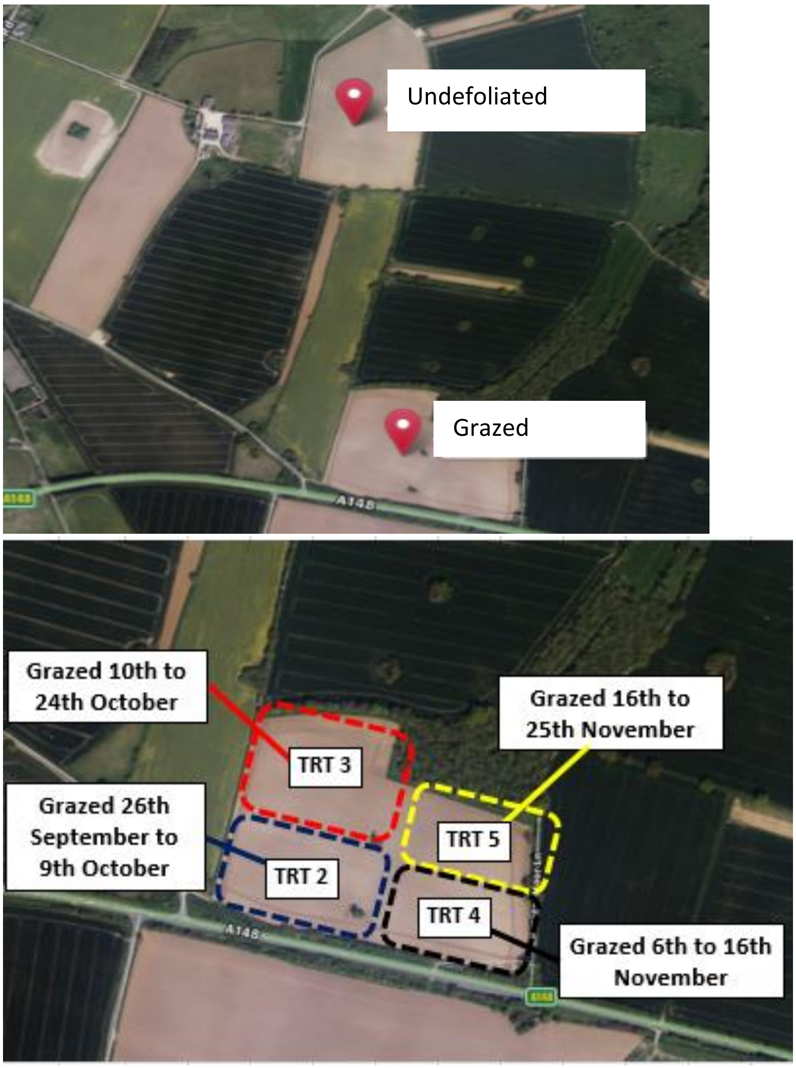

Figure 33 Site 5 undefoliated field and grazed field location (top) grazed field layout (bottom).

Appendix 2 Statistical Summary

Table 2 Statistical output for GAI (March) at all sites.

Site	Significance (P)	F value	*df*
1	<0.001	179.4	15
2	<0.001	217.54	10
3	0.01	10.12	10
4	<0.001	38.14	9
5	<0.001	9.55	15

Table 3 Statistical output for CSFB larvae (March) at all sites.

Site	*Larvae in petioles*			*Larvae in stem*			*Larvae in whole plant*		
	P	F	*df*	P	F	*df*	P	F	*df*
1	<0.001	69.05	57	<0.001	28.17	57	<0.001	84.54	57
2	<0.001	17.18	58	0.802	0.06	58	<0.001	15.49	58
3	<0.001	20.52	58	0.066	3.52	58	<0.001	24.1	58
4	<0.001	41	57	<0.001	10.42	57	<0.001	40.33	57
5	0.002	4.7	95	0.009	3.61	95	<0.001	5.22	95

7 Further reading

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