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# Predicting crop injury caused by flea beetles in spring oilseed rape through pest monitoring in the autumn

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## Abstract

1. Reliably predicting pest damage would allow farmers to reduce insecticide use without incurring economic losses and thus contribute to agricultural sustainability. However, means to predict pest severity are lacking.
2. We assessed whether crop feeding injury caused by flea beetles in spring oilseed rape can be predicted from flea beetle pest densities in the previous season using 22 years of suction trap catches of flea beetles in combination with crop feeding injury data from 293 fields.
3. We found a strong positive relationship between the densities of flea beetles of the genus *Phyllotreta* in the summer and autumn activity period of the previous year and crop feeding injury caused by flea beetles in spring oilseed rape the following year. Autumn weather or the total cover of spring oilseed rape in the study region did not improve the prediction further.
4. Pest monitoring using suction traps is thus a promising tool to predict crop feeding injury and can reduce insecticide use in years with low pest pressures.

KEYWORDS
agriculture, *Brassica napus*, crop damage prediction, flea beetle, legacy effect, neonicotinoid ban, pest management, *Phyllotreta*

## INTRODUCTION

Regulating pests is a crucial challenge in agriculture. As pest outbreaks are difficult to predict, modern agriculture relies heavily on preventative use of pesticides (Popp et al., 2013). Over the last decades, the use of systemic insecticide seed coatings against early season insect pests has increased drastically without any similar increase in pest pressures (Tooker et al., 2017). Simultaneously, evidence of the harmful effects of systemic insecticide seed coatings, particularly those containing neonicotinoids, on wild bees (Rundlöf et al., 2015), natural enemies (Douglas & Tooker, 2016) and entire food webs (Tooker & Pearsons, 2021) is gathering. Environmental and health risks have prompted policymakers to declare the goal of insecticide use reduction (Möhring et al., 2020). Following the ban of neonicotinoid seed treatments in the European Union, other systemic and non-systemic seed treatments are commonly being used in their place (Kathage et al., 2018; Lundin, 2021). Reducing the frequency in the use of insecticide seed coatings could also counteract the problematic rise in insecticide resistance in many pests (Heimbach & Müller, 2013; Tooker et al., 2017). From a farmer's perspective, avoiding insecticide seed coatings is economically feasible if it does not increase crop damage above the level of costs saved. Removing the necessity of an annual use of insecticide seed coatings on the entire cropping area would be made more viable by a reliable prediction of pest pressures.

In spring oilseed rape (*Brassica napus*), flea beetles (Coleoptera, Alticini), of the genus *Phyllotreta*, are major pests that attack plants at the cotyledon stage (Ekbom, 2010; Williams, 2010). These flea beetles overwinter as adults, emerge in early spring dependent on soil temperature, subsequently disperse across the available host crop fields in the landscape and feed on the newly emerged oilseed rape stems and cotyledons (Dosdall & Mason, 2010; Ekbom, 2010; Knodel, 2017). This early season injury to the seedlings is directly related to yield losses (Knodel, 2017; Lundin, 2020) and has so far primarily been managed by the use of systemic insecticide seed coatings (Tansey et al., 2009). After reproduction, the beetles lay their eggs on the soil near the stems and hatched larvae subsequently feed on the roots of the young plant (Dosdall & Mason, 2010; Ekbom, 2010; Knodel, 2017). After pupation, the new generation of flea beetles hatches in summer, subsequently disperses across the landscape and moves into suitable, crop or non-crop habitats for overwintering once soil starts freezing in autumn (Boetzl et al., 2023; Turnock et al., 1987).

Previous attempts to predict flea beetle pest pressure had limited success. Spring emergence is synchronised with host crop emergence and thus the time window after flea beetle assessments in spring is too narrow to inform effective crop protection (Ulmer & Dosdall, 2006). While sampling overwintering flea beetles is theoretically possible, it is time-consuming and requires an intense sampling effort due to large local variation in overwintering flea beetle densities (Burgess, 1981). Monitoring dispersing flea beetles prior to overwintering could thus be a substantial improvement. For aphids, population dynamics were monitored with tall (6–12 m) suction traps measuring long-distance dispersal rather than local activity (Harrington et al., 2007; Lagos-Kutz et al., 2020) and catches were related to aphid pressures in cereals (Fabre et al., 2010; Jonsson & Sigvald, 2016) and soybean (Rhainds et al., 2010) later in the season. Flea beetle phenology has been monitored locally within a season using 1.2–1.4 m suction traps (Augustin et al., 1986; Lamb, 1983). Tall suction traps that measure regional rather than local activity have, however, so far not been tested for predicting flea beetle pest pressure in the subsequent cropping season. Flea beetle densities in spring are determined by flea beetle populations in the autumn and the survival rate of overwintering adults. Turnock et al. (1987) found in Manitoba that autumn survival (assessed before soil freezing) was crucial in this respect rather than winter or early spring survival which was generally high for the *Phyllotreta* species studied. They identified the accumulated absolute degree day values below 0°C (freezing degree days, FDD) in autumn as an important factor, with fewer beetles emerging after warmer autumns (Turnock et al., 1987). In the frit fly (*Oscinella frit*), suction trap catches in the spring could be predicted based on the weather conditions in the preceding year (Lindblad & Solbreck, 1998). Such a relation between flea beetle densities and weather conditions could potentially be used to predict crop injury if it proves reliable.

Crop injury in spring could, however, also be affected by the total area covered by spring oilseed rape in the landscape, with the pest injury per crop plant being expected to decrease with increasing crop area due to dilution, as has been shown for other pests like the pollen beetle (Schneider et al., 2015).

We assessed whether crop injury, measured as the proportion of plants with flea beetle feeding, in the following spring can be predicted by monitoring densities of dispersing flea beetles prior to overwintering. For this, we combined 22 years of flea beetle catches from a suction trap in south-central Sweden with early-season flea beetle crop feeding injury assessments from 293 spring oilseed rape fields. We hypothesised that densities of emerging flea beetles in summer and autumn can be used to predict oilseed rape cotyledon feeding injury in the subsequent year, with flea beetle densities being positively related to cotyledon feeding injury. Additionally, we assessed whether FDD and the total area cropped with the host crop spring oilseed rape increases and decreases the cotyledon feeding injury due to increased winter survival and pest dilution, respectively.

## MATERIALS AND METHODS

### Data collection

Flea beetles were collected using a suction trap of the Rothamsted model, collecting from 12.2 m above ground level at Ultuna, Uppsala (59.817500 N, 17.65611E) with an airflow of 2800 to 3000 $m^3/h$ (Macaulay et al., 1988). This trap was established by the plant protection unit at the Swedish University of Agricultural Sciences and has been active from spring to autumn since 1984, with the collecting vials replaced three times per week during the season. Samples were available for all years between 01 May and 30 September and thus we chose these dates for inclusion in analyses. For our analyses, we used collections from 1998 to 2019, as these were the years that both species identification of flea beetles and crop injury data in the subsequent season were available. Due to the large number of samples and their rich content, we identified flea beetles from every third sample throughout the season, resulting in approximately one sample per week. Flea beetles were identified to species level and were stored in 70% ethanol in the collection of the Biological Museum of Lund University. We limited our analyses to flea beetles of the genus *Phyllotreta* that are known pests of spring oilseed rape (Ekbom, 2010).

Crop injury data for the subsequent years (1999 to 2020) was obtained from the Plant Protection Centers of the Swedish Board of Agriculture for the counties Stockholm (31 fields), Uppsala (158 fields) and Västmanland (104 fields). These three counties are similar in climate and contribute a high share in Swedish spring oilseed rape production (Lundin, 2021). The suction trap at Ultuna is located approximately in the centre of this region, with a potential maximum of 120 km to any location within the focal counties (Figure 1). In previous studies on aphid population dynamics monitored with suction traps, a similar spatial scale of 75 km was used and found relevant using the same suction trap type (Harrington et al., 2007), and even suction trap catches from traps with lower height were found to be non-independent if traps were closer than 150 km from each other (Schmidt et al., 2012). Per year, data was available from two to 25 fields (mean ± SE: 13.3 ± 1.4) with a total of 25 commercial cultivars. In each field, a plot without insecticide and fungicide application

**FIGURE 1** Map of southern Sweden (grey) with the three counties from which we analysed spring oilseed rape injury data, Västmanland, Uppsala and Stockholm (from west to east), highlighted in orange. The point indicates the location of the suction trap in Ultuna (Uppsala county) where dispersing flea beetles were caught.

was established approximately 24 m from any field edge (length 40 m, width >18 m). Crop injury was measured weekly starting with crop emergence in each plot as proportion of plants with characteristic shot-hole feeding injury caused by flea beetles (Brandt & Lamb, 1993) out of 25 plants assessed (five plants each in five randomly selected groups of plants). For each field in each year, we selected the maximum measured injury proportion up until the crop had developed four true leaves (development stage BBCH 14; Lancashire et al. (1991)), which includes the crop stage period where flea beetle attacks are most consequential for crop yield (Ekbom, 2010; Lundin, 2020). Out of these maximum values for each field, we calculated the mean spring oilseed rape feeding injury per year in the region.

To investigate potential effects of autumn climate, we obtained climate data from a weather station located in close proximity to the suction trap at Ultuna campus that is part of the LantMet network (data accessed via the LantMet database; Swedish University of Agricultural Sciences, 2022). We calculated autumn FDD as the accumulated absolute degree values of all days below 0°C (measured at 1.5 m) from 01 September to 30 November following Turnock et al. (1987). Freezing degree days were strongly negatively correlated with the mean temperature in the same period (Pearson's $r = -0.71$, $p < 0.001$). Additionally we obtained the total cover of spring oilseed rape in these three counties from the Swedish Board of Agriculture (Jordbruksverket, 2022) to account for potential pest dilution.

## Statistical analyses

All statistical analyses were performed in R 4.1.2 for Windows (R Development Core Team, 2021).

In a first step, we used a general additive model with a negative binomial residual distribution with log link (GAM; package 'mgcv', version 1.8–40; Wood, 2011) to determine the summer and autumn activity period of the flea beetle offspring across all years using the continuous flea beetle counts obtained from the suction trap. This model related the density of all *Phyllotreta* sp. individuals to the day of the year the sample was collected (included as smooth). The model additionally included two random smooths, one for year (factor) and one for year-specific effects of 'day of the year' as well as an offset on the cumulative days the trap was active for each sample (log transformed due to the log link in the residual distribution). The GAM fit was checked using the DHARMa package (version 0.4.6; Hartig, 2022) and 'gam. check' and we detected no zero inflation or violation of the model assumptions. From the bimodal GAM fit (deviance explained = 40%, k-index = 0.8), we identified the interval between 15 July and 15 September as the main summer and autumn activity period, which is in line with literature records (see Augustin et al., 1986; Lamb, 1983; Wylie, 1979; Figure 2). We confirmed by visual inspection of plots for each year that this interval covered the slight shifts in peak summer and autumn activity periods between the years.

In a second step, we related the proportion of injured plants at cotyledon stage (continuous) to the predictors: (i) average *Phyllotreta* sp. flea beetle density per day in the summer and autumn activity period of the previous year, which had been identified with the GAM fit (15 July–15 September, continuous), (ii) the total spring oilseed rape cover in the study region in the same year (continuous) and (iii) the FDD from 01 September to 30 November in the previous autumn (continuous). We included flea beetles densities both with and without the generalist *P. vittula* that feeds on and is common in oilseed rape (Lundin, 2020) but is believed to reproduce only in cereals (Ekbom, 2010). As the response was a proportion, we used beta regression models (package 'betareg', version 3.1–4; Cribari-Neto & Zeileis, 2010) with a logit link. All predictors were mean-centred and scaled as multiples of their standard deviation ($z$-scaling). Prior to inclusion in our models, we tested for correlations between all predictors and no strong correlations were detected (Pearson's $|r| \leq 0.19$, $p > 0.406$). Additionally, we checked variance inflation factors (VIF) and detected no evidence for collinearity across fixed effects in both models with VIF <1.10 (Table 1). We tested an inclusion of the respective two-way interactions but as the increase in explained variation was negligible and their inclusion worsened the model fits noticeably, we retained the simple models without interactions. The beta regression models were checked following Cribari-Neto and Zeileis (2010) and did not violate model assumptions. Model outputs were obtained using partial Wald tests via 'coeftest' and pseudo $R^2$ with the command 'performance' (package 'performance', version 0.9.1; Lüdecke et al., 2021).

# RESULTS

Across all years, the suction trap collected 2057 and 474 flea beetles of the genus *Phyllotreta* from 01 May to 30 September and in the

**TABLE 1** Total numbers of all five species of the genus *Phyllotreta* separately and combined found in the suction traps samples across the whole sampling period and in the summer and autumn activity period across all years.

| Species | Summer and autumn activity period | Total sampling period |
|---|---|---|
| *Phyllotreta atra* | 53 | 101 |
| *Phyllotreta nigripes* | 3 | 7 |
| *Phyllotreta striolata* | 8 | 89 |
| *Phyllotreta undulata* | 126 | 861 |
| *Phyllotreta vittula* | 284 | 999 |
| All *Phyllotreta* sp. | 474 | 2057 |

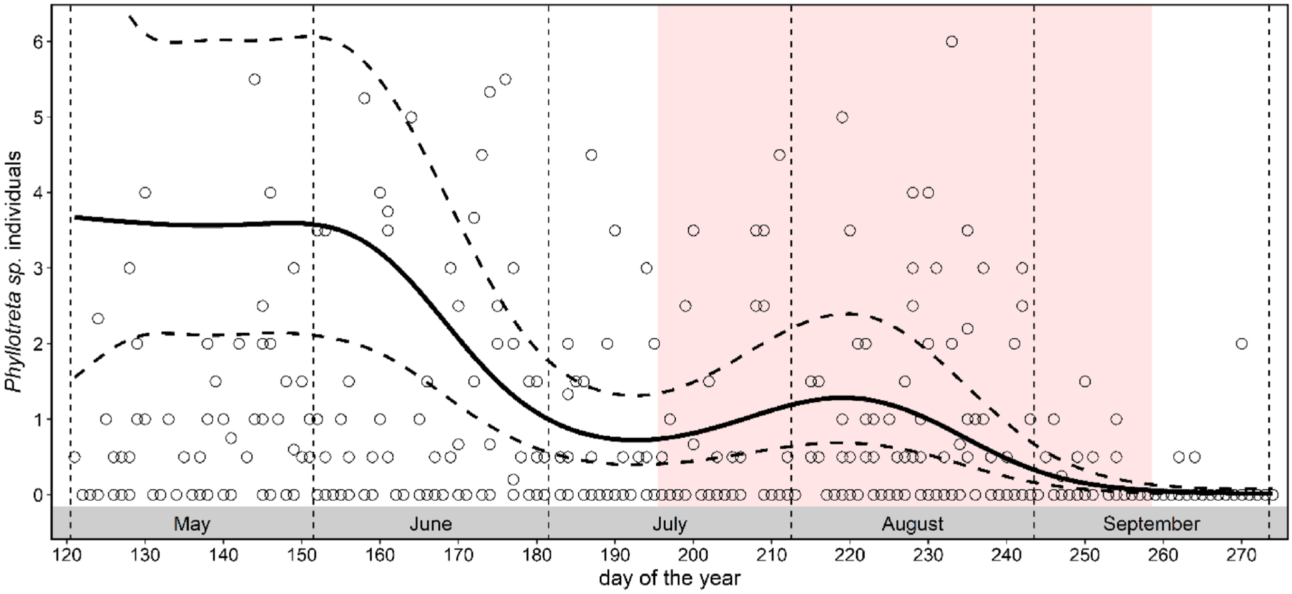

**FIGURE 2** *Phyllotreta* sp. density in suction trap samples at Ultuna from May to September in the years 1998 to 2019. The solid black line is the predicted GAM fit with 95% confidence interval (thick dashed lines). The red shaded area represents the identified approximate location of the summer and autumn activity period of the newly emerged flea beetles across all years, ranging from approximately 15 July to 15 September. The plot was cut at $y = 6.5$ to increase visibility, which leads to 14% of the values not being displayed (maximum value: 233). Thin, vertical dashed lines represent transitions between months (in a non-leap year).

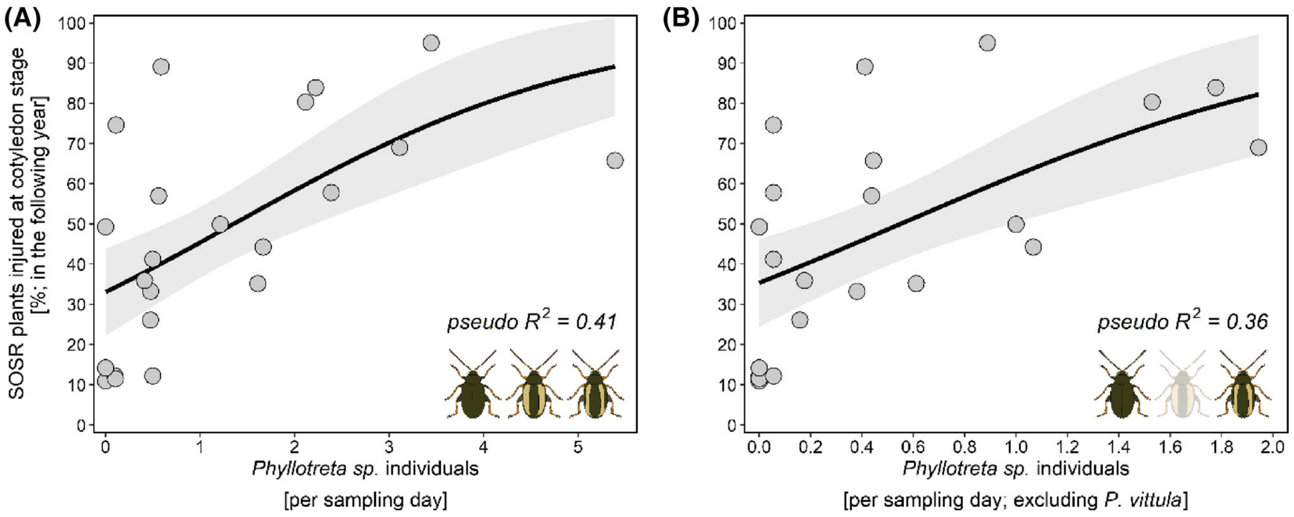

**FIGURE 3** Percent injured spring oilseed rape plants at cotyledon stage (mean in the study region) in relation to the density of (a) all *Phyllotreta* sp. individuals and (b) *Phyllotreta* sp. individuals excluding *P. vittula* in the summer and autumn activity period measured in the suction trap at Ultuna. Solid black lines are model predictions with 95% confidence interval (grey shaded area). For statistics, see Table 2.

**TABLE 2** Variance inflation factors (VIF), model coefficients and partial Wald tests for the models including all *Phyllotreta* sp. individuals and all *Phyllotreta* sp. individuals except individuals of *P. vittula* relating the proportion of injured plants at cotyledon stage in the following season to flea beetle densities in the preceding summer and autumn (measured as individuals per day), the cover of spring oilseed rape (SOSR) in the same season and the freezing degree days (FDD) in the preceding autumn.

| Predictor | VIF | Coefficient | 95% CI | Df | *z* | *p* | $R^2$ |
|---|---|---|---|---|---|---|---|
| *All Phyllotreta* sp. | | | | | | | |
| Flea beetle density | 1.06 | 0.73 | [0.33, 1.13] | 1, 17 | 3.56 | **<0.001** *** | |
| SOSR cover | 1.10 | −0.30 | [−0.69, 0.09] | 1, 17 | −1.51 | 0.131 | 0.41 |
| FDD | 1.05 | −0.03 | [−0.40, 0.34] | 1, 17 | −0.16 | 0.872 | |
| *Phyllotreta* sp. *except P. vittula* | | | | | | | |
| Flea beetle density | 1.00 | 0.66 | [0.27, 1.06] | 1, 17 | 3.29 | **<0.001** *** | |
| SOSR cover | 1.03 | −0.16 | [−0.54, 0.21] | 1, 17 | −0.85 | 0.393 | 0.36 |
| FDD | 1.03 | −0.10 | [−0.47, 0.28] | 1, 17 | −0.51 | 0.611 | |

*Note*: The predictors were mean-centred and scaled as multiples of the standard deviation in both models. Coefficients can be interpreted as changes in the log-odds ratio per 1 standard deviation of the fixed effect due to the logit link used in the models.
Abbreviations: CI, confidence interval; Df, degrees of freedom (numerator, denominator); *p*, *p*-value: ***$p < 0.001$; $R^2$, pseudo $R^2$; *z*, *z*-score returned from partial Wald tests.

summer and autumn activity period from 15 July to 15 September, respectively (Table 1). The most common species was *P. vittula* (284 individuals), followed by *P. undulata* (126 individuals), *P. atra* (53 individuals), *P. striolata* (8 individuals) and *P. nigripes* (3 individuals; Table 1). *Phyllotreta* sp. densities in the suction trap in the summer and autumn activity period ranged from 0 to 5.39 individuals per day (mean ± SE: 1.23 ± 0.30) and from 0 to 1.94 (mean ± SE: 0.50 ± 0.61) without *P. vittula*. The mean proportion of plants with feeding injury at the cotyledon stage ranged from 10.9 to 95.0% per year (mean ± SE: 47.7 ± 5.8%). The area cropped with spring oilseed rape ranged from 1122 to 20,578 ha (mean ± SE: 8344 ± 1187 ha) and FDD ranged from 0 to 70.6 (mean ± SE: 20.7 ± 4.1).

The densities of *Phyllotreta* sp. both with and without *P. vittula* in the summer and autumn activity period were positively related to the proportion of injured plants at cotyledon stage in the following spring (Figure 3, Table 2). Pseudo $R^2$ was slightly higher when *P. vittula* was included (0.41 vs. 0.36). Neither the availability of spring oilseed rape host crop in the same year, nor FDD in the previous autumn was significantly related to the proportion of injured plants at cotyledon stage (Table 2). The density of *P. vittula* was not significantly correlated with the density of the remaining *Phyllotreta* species (Pearson's $r = 0.16$, $p = 0.479$).

## DISCUSSION

Our results show that crop feeding injury caused by flea beetles could be predicted through monitoring of pest densities in the previous season. As expected, higher pest densities prior to overwintering resulted in a higher proportion of crop plants with feeding injury after overwintering. In contrast to previous monitoring attempts, this approach gives farmers sufficient time to react to expected crop injuries as compared to spring assessments (Ulmer & Dosdall, 2006) and is easier than monitoring overwintering flea beetles by soil sampling (Burgess, 1981). Despite that *P. vittula* was a dominant species, its inclusion or exclusion only marginally affected the predictive power of the model. With expected pest pressure identified in autumn, farmers would have enough time to decide whether to use insecticide-coated seeds or the less harmful and cheaper alternative without insecticide coating, based on the predicted severity of crop feeding injury. As we measured the proportion of plants with flea beetle feeding injury, whereas yield loss calculations have been based on proportion of leaf area injured (Lundin, 2020), we were unfortunately not able to relate our crop feeding injury predictions to economic thresholds. This limitation could be overcome by simultaneously measuring the proportion of plants with flea beetle feeding injury and the proportion of leaf area injured, in order to relate the two measures with each other. Our prediction of crop feeding injury was, furthermore, more reliable in years with high crop feeding injury and less reliable in years with low crop feeding injury. High flea beetle densities were never related to low crop feeding injury but low flea beetle densities were occasionally related to considerable crop feeding injury. The accuracy of crop feeding injury prediction thus needs to be increased in order to give reliable insecticide use recommendations to farmers, for example, via a more systematic monitoring of crop feeding injury and a larger network of suction traps that can better account for local differences in climate or land-use that could affect flea beetles. Nevertheless, our results show that it is generally possible to predict flea beetle feeding injury in the next season by monitoring summer- and autumn-active flea beetles before overwintering.

In contrast to Turnock et al. (1987), we did not find an effect of FDD in autumn on feeding injury caused by flea beetles in spring oilseed rape, indicating that this climate metric is not suitable for predicting feeding injury by flea beetles. According to Turnock et al. (1987), a warmer autumn period might lead to lower flea beetle survival. However, the authors also state that flea beetles in early stages of overwintering are more sensitive and thus die more easily from the experimental heating used to assess whether beetles are alive, which could lead to an overestimation of autumn mortality in overwintering flea beetles (Turnock et al., 1987). A lower FDD in autumn could have led to more beetles being in early stages of overwintering at the time of assessment and thus to an overestimation of the effect of FDD on autumn survival.

Similarly, we did not find a significant effect of total spring oilseed rape cover on spring oilseed rape feeding injury, as would be expected in the case of pest dilution, despite model estimates being negative. Pest dilution effects are usually measured directly in the landscapes where the damage is assessed (see Schneider et al., 2015 or Scheiner and Martin, 2020). It is likely that pest dilution effects are more local and could not be observed at this large, regional scale.

Several factors could have contributed to the unexplained variation in flea beetle crop feeding injury in our models. First, the weekly subsampled catches of flea beetles in the single suction trap could have been influenced by local conditions and random events. This could result in flea beetle densities being more or less accurate depending on how representative the local conditions were of the overall mean of the region in the respective year. Second, feeding injury assessments were more precise and representative in some years than in others due to a considerable variation in the number of fields monitored and likely in their geographic distance to the suction trap. A combination of a more systematic crop injury recording in the proximity of the suction traps and a simultaneous increase in the spatial extent of the flea beetle recording in existing suction traps and an expansion of the Swedish suction trap network may thus better account for local variability and improve predictions. Further evidence is needed about the dispersal distances of the flea beetle species to determine the optimal suction trap density for such a monitoring network. In addition, the flea beetle activity interval in the summer and autumn was chosen across all years. In reality, however, the interval will shift depending on climatic conditions in each year and predictions may be more precise if intervals are selected within each year. The extent of our dataset unfortunately did not allow us to do this as some years had very low summer and autumn activity which made an identification of the start and end of the intervals impossible. Despite these uncertainties and limitations, we were able to relate flea beetle densities in the summer and autumn activity period to crop feeding injury in the next season with reasonable confidence as our models explained a considerable share of the variation in the data.

Our analyses are a first step towards predicting crop damage in the next season by monitoring pests at an ecologically meaningful point in time. However, we also show that there is considerable potential for improvement of the reliability of these predictions. For flea beetles, a network of suction traps could be used to predict pest pressures more locally and thus likely more precisely. The same networks could also be used to monitor other pests that have some form of long-distance dispersal as a key factor in their life cycles, such as aphids or frit flies, and can be used to predict pest pressures and resulting crop damages (Jonsson & Sigvald, 2016; Lindblad & Solbreck, 1998). With more precise predictions, crop advisers and farmers could ultimately decide when and where it is necessary and economically feasible to use insecticide seed coatings. Such a system could result in a reduction in overall insecticide use and thereby contribute to the pesticide reduction goals of European policymakers (Möhring et al., 2020).

## AUTHOR CONTRIBUTIONS

**Fabian Alexander Boetzl:** Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft; writing – review and editing. **Mattias Jonsson:** Data curation; funding acquisition; methodology; resources; supervision; writing – review and editing. **Velemir Ninkovic:** Data curation; funding acquisition; methodology; resources; supervision; writing – review and editing.

**Roland Sigvald:** Data curation; methodology; resources; writing – review and editing. **Carol Högfeldt:** Data curation; resources; writing – review and editing. **Gerard Malsher:** Data curation; resources; writing – review and editing. **Ola Lundin:** Conceptualization; investigation; project administration; resources; supervision; validation; writing – review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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