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Pest management and yield in spring oilseed rape without neonicotinoid seed treatments

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ABSTRACT

Use of neonicotinoid insecticides as seed treatments has been prohibited in the EU. As a consequence, concerns of lost production have been raised among producers. It remains, however, unclear to what extent the ban has increased pest attacks and crop damage, and reduced yield and farm profit. It is also unclear to what extent alternative, non-chemical options can protect crops. Flea beetles (Chrysomelidae: Alticini) are the main pests targeted by insecticide seed treatments in spring oilseed rape (*Brassica napus* L.). Over three years, we conducted 23 field experiments in which we compared seeds treated with neonicotinoids with untreated seeds, grown at normal or doubled sowing rates. The experiments were established during a range of sowing times at the same time as the hosting farmer sowed, which also allowed us to assess the impact of sowing date. We measured flea beetle activity density, crop plant density, cotyledon damage, crop yield and relative economic performance. Flea beetle activity density was eight times higher in 2014 than in 2016, with intermediate activity in 2015. Neonicotinoid seed treatment, increased sowing rate and an earlier sowing date all reduced crop damage. Seed treatment decreased crop yield loss by 521 kg ha^{-1} and relative profit loss by 144 Euro ha^{-1} in 2014, but had no effect on yield or profit in 2015–2016. Increased sowing rate did not affect yield, but decreased profit in 2015 (−138 Euro ha^{-1}) and 2016 (−114 Euro ha^{-1}), mainly due to higher costs for seed. Earlier sowing date was consistently associated with higher yield and profit. Our results put prophylactic seed treatments in question, as they gave lower yield losses in only one year out of three. Earlier sowing and somewhat higher sowing rate emerge as viable alternative pest management practices. Because management outcomes depended on pest pressure, which varied from year to year, crop damage prognosis tools are needed based on improved understanding of the population ecology of crop pests, to support the growers' decisions and avoid unnecessary use of insecticides.

1. Introduction

Outdoor use of seeds treated with neonicotinoids, a widely used and versatile class of insecticides (Jeschke and Nauen, 2008; Simon-Delso et al., 2015), has been banned in the EU (European Commission, 2019) because of observed negative impacts on pollinating insects (Rundlöf et al., 2015; Woodcock et al., 2016, 2017). Concerns have been raised about lost production and reduced competitiveness of European farming following a ban (Noleppa and Hahn, 2013). It is, however, unclear to which extent treating seeds with neonicotinoids or other insecticides reduce crop damage and yield loss, and increase farm competitiveness (Goulson, 2013; Godfray et al., 2014; but see Kathage et al., 2018). Such information is needed to weigh benefits against the risks of insecticide use.

Despite hard historic lessons of indiscriminate insecticide use leading to pesticide resistance, secondary pests and environmental degradation (van den Bosch, 1978), widespread use of insecticide seed treatments has entailed a return to prophylactic use of pesticides, thereby derailing a basic integrated pest management principle of employing pesticides only as a last resort (Douglas and Tooker, 2015). When pesticides are available for use, there is limited support for research and development of alternative and complementary pest management practices. As a consequence, growers are left without crop protection options when negative environmental consequences of pesticides are revealed and their use is prohibited, as for neonicotinoids in the EU (European Commission, 2019). New ways to protect the crop become urgently needed.

Oilseed rape (*Brassica napus* L.) is attacked by a number of insect

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pests, to the extent that they constitute a main production-limiting factor in many regions (Williams, 2010; Dosdall and Mason, 2010; Dewar, 2017; Kathage et al., 2018). In Europe, neonicotinoid seed treatments in oilseed rape have mainly targeted cabbage stem flea beetles (*Psylliodes chrysocephala* L.) and green peach aphids (*Myzus persicae* Sulzer) in winter oilseed rape (Budge et al., 2015; Zhang et al., 2017), and flea beetles (*Phyllotreta* spp.) in spring sown oilseed rape (Ekbom, 2010). The latter are recurring and often serious pests at crop emergence, and seed treatments have been used for decades for flea beetle control (Ekbom, 2010). Non-chemical management options to reduce yield losses to flea beetles in spring oilseed rape have been suggested. Increased sowing rates reduce crop damage caused by flea beetles (Dosdall et al., 1999; Dosdall and Stevenson, 2005). It is, however, unclear whether lower crop damage also translates into yield benefits, and if so whether income gains due to higher yields exceed the increased costs for seed at higher sowing rates. Another promising pest management option is to sow earlier in the season such that crop emergence does not coincide with peaks in flea beetle activity, and the seedling has passed the more sensitive early growth stages when the flea beetles arrive. Small plot manipulations with early sowing reduced damage by flea beetles and gave higher yield (Myrbeck, 2017; Lundin et al., 2018). However, the effects of sowing date at the scale of commercial fields remain to be assessed.

Our aim was to test the effects of increased sowing rates and earlier sowing date as alternatives to insecticide seed treatment for control against flea beetles in spring oilseed rape. We performed factorial field experiments at 23 sites over 3 years (2014–2016) in which we compared neonicotinoid treated seeds with untreated seeds, grown at normal or doubled sowing rates. The experiments were sown at the same time that the hosting farmer sowed, rendering a range of sowing dates that allowed us to assess impacts of sowing time at the scale of commercial fields. We measured the effects on flea beetle activity density, crop plant density, pest damage, crop yield and relative economic profit.

2. Materials and Methods

We conducted the experiments between 2014 and 2016 in south central Sweden, in the vicinity of the cities Uppsala, Stockholm and Västerås, a region historically known to suffer damage by *Phyllotreta* spp. flea beetles in spring oilseed rape (Ekbom and Müller, 2011). We established a total of 23 field experiments in 2014 (n = 6), 2015 (n = 8) and 2016 (n = 9). Within each year, the distance between field experiments was at least 6 km. Each experiment consisted of four blocks. In each block we sowed a plot with treated seeds at the normal sowing rate, a plot sown with untreated seeds at the normal sowing rate and a plot sown with untreated seeds at twice the normal sowing rate, for a total of 12 plots per experiment. Each plot was 12 by 3.75 m. We used the hybrid spring oilseed rape cultivars Majong (SW) in 2014–2015 and Mirakel (NPZ) in 2016. The seed treatments used under experimental permit were Elado (Bayer; 25 ml per kg seed: 400 g l^{-1} clothianidin, 80 g l^{-1} β-cyfluthrin) in 2014–2015, and Cruiser OSR (Syngenta; 15 ml per kg seed: 280 g l^{-1} thiamethoxam, 8 g l^{-1} fludioxonil, 32.3 g l^{-1} metalaxyl-M) in 2016. We had to change cultivar and insecticide treatment in 2016 because of changes in availability of treated seeds. The two sowing rates that we tested were the normal recommended for hybrid cultivars of 150 seeds per square meter or 300 seeds per square meter. The normal recommended seeding rate of 150 seeds per square meter was based on official Swedish field trial results (Gunnarson, 2013).

We placed the field experiments within commercial fields of spring oilseed rape, with two exceptions: in 2014 one experiment was placed on university-owned land next to another spring oilseed rape experiment, and in 2015 one experiment was placed inside a commercial linseed (*Linum usitatissimum* L.) field due to a shortage of spring oilseed rape fields. We typically placed the field experiments 20–40 m from the field border. The experiments were sown by a contracted field team at the same time as the surrounding crop was sown by the hosting farmer. Each experiment received NPK fertilisers at sowing as per standard practice, at levels corresponding to those used in the rest of the field. No foliar insecticides against flea beetles were used inside the perimeters of the field experiment. Apart from that, the hosting farmers managed the experiment and the rest of the field identically, following their standard farm management operations. This typically included applying herbicides to control weeds, and insecticides against, for instance, pollen beetles (*Meligethes aeneus* F.) later in the season.

2.1. Flea beetles

We monitored flea beetles (Coleoptera: Alticini) in each field experiment using four pitfall traps (diameter = 115 mm, Perez-Alvarez et al., 2018). We placed one pitfall trap at each of the four corners of the field experiment at each site. We only monitored flea beetles at each experiment, and not within each experimental treatment plot due to the relatively small plot sizes across which the flea beetles could easily move. The purpose of the site-level pitfall trapping was to characterise the flea beetle community, and to test for variation in flea beetle activity depending on year and sowing date. The traps were placed approximately 1 m into the experiment, in 3.75 m wide buffer zones sown at the edges of experimental plots with untreated seeds of spring oilseed rape. We dug down the pitfall traps before the crop had emerged, within approximately one week after sowing. We emptied the pitfall traps every second to fourth day until the crop had two true leaves, which was 24–40 days after the sowing date, depending on crop growth rate. This corresponds to the main critical period for flea beetle crop damage; damage inflicted later in the season rarely has any economic impact (Dosdall and Mason, 2010). We counted flea beetles caught and identified them to the lowest taxonomic resolution possible, following Hansen (1927) and Landin (1971). In 2014, 2015, we subsampled and identified 20 flea beetles in samples that had more than 20 flea beetles, and extrapolated the species distribution to the whole sample, whereas in 2016 we identified all flea beetles collected. We summed flea beetle numbers across traps and sampling days within each experiment prior to statistical analyses. Thus, we used a single measure per field, total number of flea beetles caught, as our response variable for flea beetle activity density.

2.2. Crop plant density and crop damage

We monitored crop plant density and cotyledon damage from crop emergence (crop phenological development stage BBCH 10, Biologische Bundesanstalt, Bundessortenamt und Chemische Industire, Lancashire et al., 1991) until the crop had two true leaves (BBCH 12). We visited fields every second to fourth day during this period, giving a total of 6–10 visits per experiment, depending on crop growth rate. To ensure that visit number denoted the same approximate growth stage irrespective of field identity (i.e. visit number 1 = cotyledons unfolded, visit number 10 = two fully developed true leaves), we adjusted the visit number for fields visited less than 10 times by multiplying the visit number by ten over the total number of visits to that field, and then rounding to the nearest integer. At each visit, we counted the number of plants in four 0.25 m^2 quadrats per plot, and assessed cotyledon damage on 20 plants per plot. Flea beetles cause characteristic cotyledon damage (Brandt and Lamb, 1993), which we classified into five categories: 0 = 0% of cotyledon area damaged, 1 = 1–10%, 2 = 11–30%, 3 = 31–60%, and 4 > 60% of cotyledon area damaged (modified from Ekbom and Kuusk, 2005). Classifications of cotyledon damage were converted to proportions using the centre point in each damage class (0 = 0, 1 = 0.055, 2 = 0.205, 3 = 0.455 and 4 = 0.805). Crop plant densities and cotyledon damage were averaged per plot and visit number prior to statistical analyses.

2.3. Oilseed rape yield

We harvested a 10 m by 2 m area at the centre of each plot and weighed the seed yield with experimental threshers near the time of commercial harvest of the field. Two and a half of the 23 field experiments were, however, not harvested. In one case in 2014, heavy flea beetle damage caused the farmer to abandon the oilseed rape crop and instead plant barley. Because management of the experiment and surrounding crop was coordinated by the farmer (see above), this meant that the experiment could not be maintained until harvest. A further experiment in 2014 was heavily damaged by flea beetles and due to a misunderstanding, the hosting farmer did not treat the experimental area with herbicides, leading to such large numbers of weeds that only seed treated plots could be harvested. In 2015, the crop in one experiment was destroyed by clubroot (*Plasmodiophora brassicae*). The loss of yield data led to an underestimation of the benefits of seed treatment in 2014, as the loss of data (no harvestable crop) was due to the excessive insect pest pressure. Conclusions for 2015 and 2016 are unaffected. A sample of seeds from each harvested plot was rinsed and analysed for water and oil content using near-infrared transmittance (AgriLab, Uppsala, Sweden). We standardised all plot yields to kg per ha of rinsed seed with 9% water content.

2.4. Economic analysis

We performed a partial profit analysis in which yield payments were offset against costs of seed and seed treatment, for each treatment. Publicly available data was used for the yield base price, seed cost and seed treatment cost (www.sverigeforsoken.se). We rendered calculations in Euros, applying an exchange rate of 10 Swedish kronor (SEK) per Euro. We based yield payment on Swedish commercial price setting rules (Lantmännen, 2017) which is based on price per kg of seed: 0.271, 0.311 and 0.333 Euros per kg in 2014, 2015 and 2016 respectively. This yield base price is adjusted upward by 1.5% for each percentage point of oil over 40%, and downward by 1.5% for each percentage point of oil below 40%. If the water content of the crop is above 9%, the oil adjustment is calculated at 9% water. If the water content of the crop is below 9%, the oil adjustment is calculated at the actual water content. A rinsing fee also applies, ranging from zero if the amount of material that needs to be rinsed from the crop is below 2% by weight, to 30 Euro per 1000 kg if the amount exceeds 20%. We used a seed cost of 107.1 and 214.2 Euro per hectare for the normal and doubled sowing rate respectively. A cost for neonicotinoid seed treatment was difficult to estimate because the Swedish market shifted from exclusively using treated seed in 2013 to exclusively using untreated seed from 2014 onwards. As a conservative estimate of the cost, we used the 2013 price difference between seeds treated with Chinook (Bayer; 20 ml per kg seed: 100 g l^{-1} imidacloprid, 100 g l^{-1} β-cyfluthrin), an older and less effective seed treatment (Ekbom and Müller, 2011), and seeds treated with Elado. This price difference was 1.7 Euros per kg seed, which equates to 13.6 Euros per hectare at the recommended sowing rate, assuming a seed weight of 5.33 g per 1000 seeds. This cost per hectare is similar to what has been estimated for neonicotinoid seed treatments in winter oilseed rape in the UK (Nicholls, 2013). We did not include in the analysis expenses that were constant across treatments, such as those for machinery, labour, fertiliser, herbicides and insecticides not targeted at flea beetles.

2.5. Statistical analyses

We analysed data using general and generalised linear and linear mixed models in SAS 9.4 for Windows (SAS Institute Inc., Cary, NC). The Kenward-Roger method was used to estimate degrees of freedom (Littell et al., 2006). We simplified models by sequentially removing non-significant ($p > 0.05$) factors.

We analysed flea beetle activity density in a model with year as a fixed factor and sowing date as a covariate. We further included the interaction between sowing date and year. Sowing date was standardised within year by subtracting the day number for the experiment sown first in that year from the sowing day number. The date for the earliest sown experiment was April 24, April 15 and May 2 in 2014, 2015 and 2016 respectively. We used a negative binomial distribution with a log link, and the ln-transformed number of trap-days was included as an offset in the analysis.

Crop plant density, proportion crop damage, yield and relative profit were analysed with year and treatment as fixed factors; and sowing date, standardised within year as described above, as a covariate. We used normal distribution with identity links for these response variables. Proportion crop damage was logit-transformed prior to analysis, with the smallest non-zero value in the dataset added to both the numerator and denominator of the logit function, in order to handle zeros (Warton and Hui, 2011). Experiment identity and block within experiment were random factors. Visit number was a repeated factor using a compound symmetry covariance structure in the models for crop plant density and proportion crop damage. Covariance structure was chosen as a result of balance between model realism and complexity, where models with more complex covariance structures generally did not converge. We included all two-way interactions between predictors that included year. For response variables where there was a significant treatment by year interaction, the treatment effect was examined separately for each year using the slice option. Statistically significant ($p < 0.05$) treatment effects were followed by pairwise comparisons with Tukey adjustment.

3. Results

3.1. Flea beetles

Of the 17 species found, *Phyllotreta atra, P. striolata, P. vittula* and *P. undulata* dominated the community of flea beetles (Table 1). Flea beetle activity density varied across years (Table 2) and was highest in 2014 (33 flea beetles per trap-day, 95% confidence interval: 20–54), intermediate in 2015 (9, 6–14) and lowest in 2016 (4, 3–6). Fields with earlier sowing dates had lower flea beetle activity densities. This effect did not change significantly from year to year, although flea beetle activity was low in all experiments in 2016 (Fig. 1a, Table 2).

3.2. Crop plant density and crop damage

The treatment effect on both crop plant density and proportion crop

Table 1
Flea beetle community composition in 23 spring oilseed rape fields in Sweden 2014–2016. Number of individuals caught in pitfall traps in all field experiments by year.

Species	2014	2015	2016	Total
Phyllotreta atra Fabricius	7728	3111	209	11,048
P. striolata Fabricius	7978	945	168	9091
P. vittula Redtenbacher	4321	2607	556	7484
P. undulata Kutschera	3135	569	504	4208
P. nigripes Fabricius	892	162	25	1079
P. nemorum L.	9	16	0	25
P. armoraciae Koch	13	0	0	13
P. ochripes Curtis	6	0	0	6
Aphthona euphorbiae von Schrank	526	1326	799	2651
Chaetocnema spp.	1177	1030	303	2510
Longitarsus sp.	10	400	101	511
Lythraria salicariae von Paykull	0	21	6	27
Sphaeroderma testaceum Fabricius	0	10	0	10
Aphthona lutescens Gyllenhaal	0	0	6	6
Hippuriphila sp.	0	6	0	6
Batophila rubi von Paykull	0	5	0	5
Mantura rustica L.	1	0	2	3
Total	25,796	10,209	2679	38,684
Sampling effort (trap days)	811	956	714	2481

Table 2
Statistical tests for effects of treatment (untreated control, seed treatment and doubled sowing rate) and sowing date on flea beetle activity density (flea beetles per trap-day), crop plant density (plants per square meter), proportion crop damage to cotyledons, yield (kg seeds per hectare at 9 percent water content) and relative profit (yield payments minus costs for seed). In cases when the overall treatment by year effect was statistically significant ($p < 0.05$), test statistics were estimated for each year separately using the slice option. Flea beetle activity densities were not measured for each treatment separately.

Response variable:	Flea beetles		Crop plant density		Crop damage		Yield		Relative profit	
Predictor variable:	F_{df}	p	F_{df}	p	F_{df}	p	F_{df}	p	F_{df}	p
Year	$22.87_{2,19}$	**< 0.0010**	$9.11_{2,20}$	**0.0015**	$11.41_{2,19}$	**< 0.0010**	$12.75_{2,17.2}$	**< 0.0010**	$20.71_{2,17.1}$	**< 0.0010**
Treatment	–	–	$219.22_{2,177}$	**< 0.0010**	$205.99_{2,171}$	**< 0.0010**	$15.56_{2,156}$	**< 0.0010**	$73.19_{2,156}$	**< 0.0010**
Treatment × Year	–	–	$8.97_{4,177}$	**< 0.0010**	$2.70_{4,172}$	**0.032**	$6.90_{4,156}$	**< 0.0010**	$6.41_{4,156}$	**< 0.0010**
2014: Treatment	–	–	$32.56_{2,173}$	**< 0.0010**	$80.73_{4,161}$	**< 0.0010**	$20.62_{2,157}$	**< 0.0010**	$28.25_{2,157}$	**< 0.0010**
2015: Treatment	–	–	$89.30_{2,181}$	**< 0.0010**	$72.65_{4,178}$	**< 0.0010**	$1.66_{2,156}$	0.19	$32.34_{2,156}$	**< 0.0010**
2016: Treatment	–	–	$137.40_{2,177}$	**< 0.0010**	$53.33_{4,179}$	**< 0.0010**	$0.83_{2,156}$	0.44	$29.35_{2,156}$	**< 0.0010**
Sowing date	$6.38_{1,19}$	**0.021**	$1.86_{1,19.2}$	0.19	$5.68_{1,19.1}$	**0.028**	$16.07_{1,17.2}$	**< 0.0010**	$12.61_{1,17.2}$	**0.0024**
Sowing date × Year	$1.81_{2,17}$	0.19	$3.57_{2,17}$	0.051	$2.24_{2,17}$	0.14	$0.64_{2,15.2}$	0.54	$0.62_{2,15.2}$	0.55

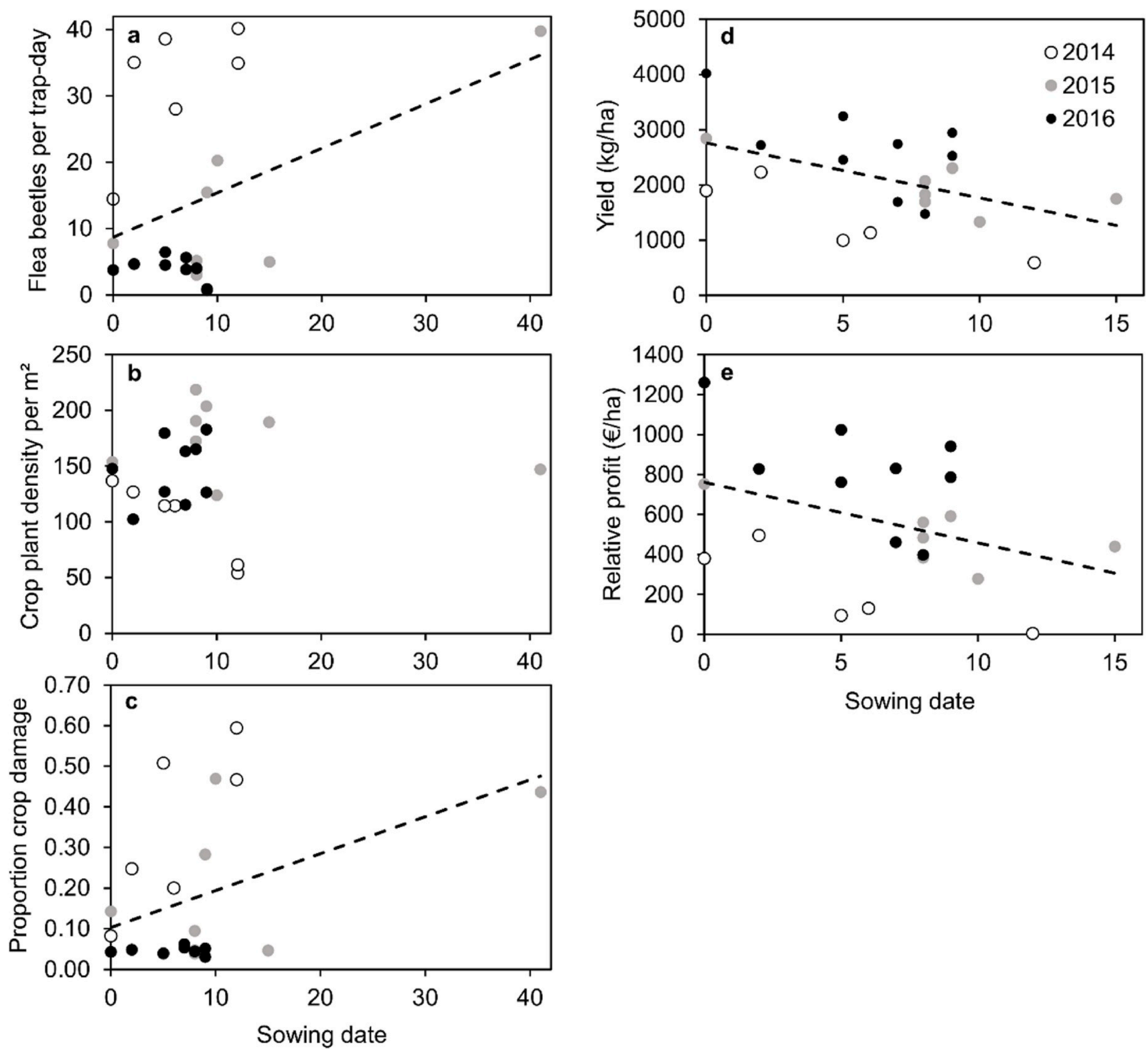

Fig. 1. Early sowing gave (a) lower flea beetle activity density during crop establishment, (b) did not affect crop plant density, (c) decreased proportion cotyledon crop damage, and (d) gave higher yield (kg seeds per hectare at 9 percent water content, and (e) relative profit (yield payments minus costs for seed). Sowing date was standardised within year by subtracting the day number for the experiment sown first in that year from sowing day number. Each data point represents an experiment mean (n = 23 in a-c, n = 21 in d-e). Trend lines are simple linear regressions shown for statistically significant ($p < 0.05$) relationships for visual aid in interpretation, but statistical tests were based on linear mixed models, as described in Materials and Methods.

damage varied among years (Table 2). Doubled sowing rate led to highest plant density in all three years, whereas seed treatment reduced plant density loss relative to the untreated control in 2014, but not in 2015–2016 (Fig. 2a–c). Sowing date did not affect plant density, although there was a trend for a sowing date by year interaction (Fig. 1b, Table 2). Seed treatment consistently decreased proportion crop damage relative to other treatments (Fig. 2d–f). When pooled over all three years, doubled sowing rate reduced crop damage relative to the

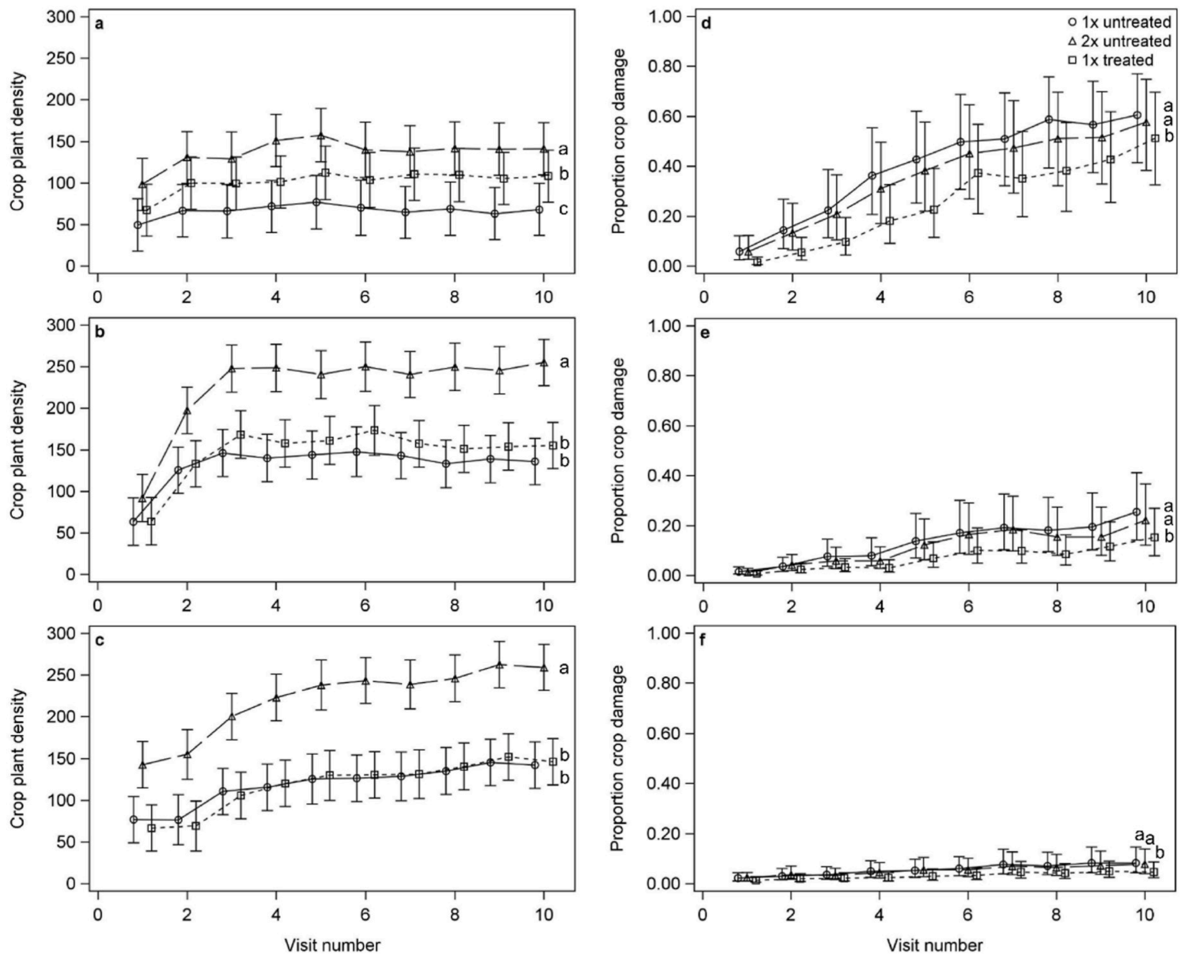

Fig. 2. Crop plant density (plants per square meter) and proportion crop damage in (a, d) 2014, (b, e) 2015 and (c, f) 2016. Doubling the sowing rate (2× untreated) gave (a–c) the highest number of crop plants per square meter each year, whereas seed treatment (1× treated) gave lower plant density loss compared to untreated seeds grown at normal sowing rate (1× untreated) in 2014, but not 2015–2016. Seed treatment gave (d–f) the lowest proportion crop damage to cotyledons in all three years. Doubled sowing rate numerically decreased crop damage relative to the untreated control in all three years, but damage reduction was only statistically significant when all three years were pooled (see text). Visit number 1 corresponds to the crop stage when cotyledons have unfolded (BBCH 10) and visit number 10 to when two true leaves have been fully developed (BBCH 12). Error bars indicate 95% confidence intervals. Treatments labelled with different letters within a year are significantly ($p < 0.05$) different when averaged across visit numbers.

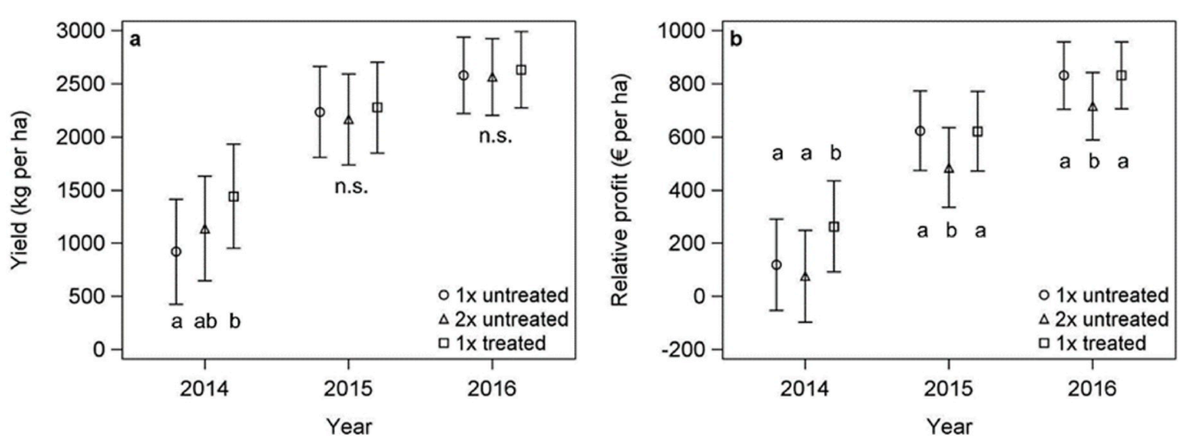

Fig. 3. Seed treatment (1× treated) decreased (a) oilseed rape yield loss (kg seeds per hectare) relative to untreated seeds grown at normal sowing rate (1× untreated) in 2014, whereas yield did not differ among treatments in 2015–2016. Seed treatment reduced (b) relative profit loss (yield payments minus costs for seed) relative to other treatments in 2014, whereas untreated seeds grown at twice the normal sowing rate (2× untreated) decreased profit relative to other treatments in 2015–2016. Error bars indicate 95 percent confidence intervals. Treatments labelled with different letters within a year are significantly ($p < 0.05$) different. n.s. = no significant differences.

untreated control ($F = 10.01_{1,171}$, $p = 0.0018$), but when each year was analysed separately, doubled sowing rate exhibited crop damage levels that were numerically lower but statistically indistinguishable from those in the untreated control (Fig. 2d–f). Fields with earlier sowing date had lower crop damage. This effect did not change significantly from year to year, although crop damage was low in all experiments in 2016 (Fig. 1c, Table 2).

3.3. Crop yield and economic analysis

The treatment effect varied among years for both yield and relative profit (Table 2). Seed treatment reduced yield loss relative to the untreated control in 2014, whereas yield did not differ among treatments in 2015–2016 (Fig. 3a). Seed treatment also decreased relative profit loss compared with other treatments in 2014, whereas untreated seeds grown at twice the normal sowing rate decreased relative profit compared with other treatments in 2015–2016 (Fig. 3b). Fields with earlier sowing date consistently had higher yields and profits (Fig. 1d and e, Table 2).

4. Discussion

Seed treatment with neonicotinoid insecticides against flea beetles were only economically justified in one year out of three. We further demonstrate that sowing crops early in the season and increasing sowing rate reduce crop damage. Together with our recent finding that no-till greatly reduces flea beetle activity and crop damage (Lundin, 2019), these results illustrate that there is a toolbox of non-chemical options available for integrated pest management of flea beetles in spring oilseed rape.

Oilseed rape yields were highest in 2016, intermediate in 2015, and lowest in 2014, a variation mirroring the year-to-year variation in flea beetle abundance and crop damage. Neonicotinoid seed treatments decreased crop damage, confirming a target effect against flea beetles (Soroka et al., 2008), but did not prevent damage from exceeding the economic injury level at ca 10 percent crop damage to cotyledons (Lundin, 2020) in 2014 when pest pressure was high. There was a reduced yield loss of approximately 500 kg per ha and reduced economic loss of around 140 Euro per ha from neonicotinoid seed treatments, but only in 2014 when pest pressure was high. The economic net benefit from insecticide seed treatments have shown large yearly variation also in winter oilseed rape (Budge et al., 2015), and our results suggest that this pattern is due to year-to-year variation in pest pressure. We conducted our experiments in the part of Sweden where flea beetles typically cause the most severe crop damage (Ekbom, 2010). Prophylactic use of seed treatments in spring oilseed rape in other regions of Sweden, which was commonplace until 2014, are even less likely to be warranted. In summary, our results illustrate that prophylactic use of insecticide seed treatments against flea beetles on the entire cropping area every year would not be necessary if improved prognosis tools for flea beetle crop damage existed.

We found early sowing and increased sowing rates to be promising non-chemical practices to manage flea beetle crop damage. Yields were consistently higher in early sown fields, even in 2016 when flea beetle activity was low. Adjusting the sowing date did not incur any direct costs and thus also consistently benefited farm income. This suggests that early sowing is beneficial for yield irrespective of pest pressure. The higher numbers of flea beetles in fields sown later in the season could be related to either a prolonged period of flea beetle colonisation during spring, allowing populations to gradually build up, or that flea beetles become more active later in the season due to the generally higher temperatures (Lundin et al.,2018). Other research based on plot experiments has found mixed effects of sowing date on flea beetle activity and crop damage (Lamb, 1984; Milbrath et al., 1995; Dosdall and Stevenson, 2005; Cárcamo et al., 2008; Knodel et al., 2008; Pavlista et al., 2011). There is also a risk that frost damages the crop if sown too early. We suggest farmers to move towards sowing earlier rather than late, but an important next step is to identify a suitable time window for sowing through a comparison of temperature sums required for flea beetle activity *versus* crop growth, complemented with analysis of historic weather data to calculate the frost damage risk of sowing early.

A doubled sowing rate led to a higher number of established crop plants and also reduced crop damage, probably caused by a dilution effect where damage is spread over more plants (Dosdall et al., 1999; Dosdall and Stevenson, 2005). The reduction in crop damage was, however, modest and the increased sowing rate did not increase yield, although there was a yield gain tendency in 2014 when pest pressure was high. The economic analysis also illustrated that an increased sowing rate is currently a costly management option. A doubled sowing rate, as tested here, is unlikely to be economical for the farmer in practice unless seed prices are reduced. However, sowing rates which are slightly above the current recommended rate of 150 seeds per square meter deserve further attention.

Flea beetle activity density varied greatly between years and was high in 2014, intermediate in 2015 and low in 2016. Despite their potentially huge impact on crop damage and yield, as seen in 2014, surprisingly little is known about flea beetle population dynamics. Flea beetles are known to thrive under warm and dry weather (Burgess, 1977), but the weather in May, which is the main period during which the crop emerges, was warmer and drier in 2016 compared with 2014, and no other obvious weather pattern could explain the interannual variation in activity densities. We noted also a surprisingly diverse flea beetle community, including 17 species with four dominating *Phyllotreta* species: *P. atra*, *P. striolata*, *P. undulata* and *P. vittula*. This contrasts with earlier findings from Sweden and Estonia where *P. undulata* dominated (Ekbom, 1990, 1991; Metspalu et al., 2014). Both the long term population dynamics and ecological differences among closely related flea beetle species that attack spring oilseed rape crops in Europe deserve further attention.

Several pest management decisions, such as whether to plant treated or untreated seed or altering crop sowing rate, are made early in the season. Yet our results show that effect on yield and profit varies depending on pest pressure, which is only known retrospectively. Our results add to amassing evidence that employment of insecticide seed treatments exceeds economically justified use in major field crops, including soybean, sunflower and maize (Bredeson and Lundgren, 2015; Krupke et al., 2017a, 2017b; but see Hurley and Mitchell, 2017). In order to reduce insecticide seed treatment use, the decision whether to use them need to be supported by pest prognosis tools founded on an improved understanding of the population ecology of the pests and, in particular, drivers of abundance variation from year to year. This has hitherto proven to be difficult for flea beetles in spring oilseed rape/canola (Sekulic and Rempel, 2016), but compiling long term monitoring data on flea beetles would be a first step in this direction. We also recommend further evaluation of the merits and environmental effects of insecticide seed treatments, compared with the more classical approach of combining monitoring with use of spray insecticides when economic thresholds are exceeded.

Author contributions

OL and RB designed and acquired funding, GM, CH, and OL collected and cured the data including species determinations, OL led the data analysis and all authors contributed to interpretation of results. OL and RB wrote the article and all authors reviewed and commented on manuscripts.

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