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Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Kreutzwaldi 1, Tartu 51014, Estonia
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Flea beetle (Chrysomelidae: Alticinae) species composition and abundance in different cruciferous oilseed crops and the potential for a trap crop system

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Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Kreutzwaldi 1, Tartu 51014, Estonia

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Flea beetles are significant insect pests of cruciferous oilseed crops in northern Europe. A two-year small-scale field experiment was performed to determine the species complex and abundance of flea beetles (Chrysomelidae: Alticinae) associated with eight cruciferous oilseed plants: *Brassica juncea* (L.) Czern., *Brassica napus* L. var. *oleifera* subvar. *annua*, *Brassica nigra* (L.) Koch, *Brassica rapa* L. var. *oleifera* subvar. *annua*, *Camelina sativa* (L.) Crantz, *Eruca sativa* Mill., *Raphanus sativus* L. spp. *oleifera* (DC) Metzg. and *Sinapis alba* L. Their relative attractiveness to flea beetles was compared to assess their potential for use within a trap crop system for spring oilseed rape. Adults of six species of flea beetles were found on the test plants. *Phyllotreta undulata* Kutsch. was the most abundant species followed by *Phyllotreta nigripes* (Fabr.), *Phyllotreta nemorum* L. and *Phyllotreta vittata* (=*striolata*) (Fabr.), while *Phyllolotreta atra* (Fabr.) and *Chaetocnema concinna* Marsh. were occasionally present.

The species composition of flea beetles on seven of the investigated plant species was fairly similar but differed significantly on *C. sativa*. The flea beetle species discriminated between the tested host plants, with a general gradient in attraction from *E. sativa* > *B. juncea* > *B. nigra* > *R. sativus* > *S. alba* > *B. rapa* > *B. napus* through to *C. sativa*. *Brassica juncea* and *B. nigra* developed faster and at early growth stages were more attractive to overwintered adult flea beetles than *B. napus* and therefore had potential as trap plants to protect spring rape. *R. sativus* and *E. sativa*, despite their development rate being slower than *B. napus* were also more attractive to flea beetles. Thus, further experiments with a complex of attractive early season and late-season plant species (multiple trap crops) should be undertaken.

Keywords: cruciferous oilseed plants; flea beetles; species composition; host plant attractiveness; trap crops

Introduction

Flea beetles (Chrysomelidae) are serious and widespread pests in the world. Many species prefer plants belonging to the family of Brassicaceae (Cruciferae; Nielsen 1988; Aslan & Gök 2006). Adults of cruciferous flea beetles overwinter primarily in leaf litter and turf of shelterbelts, emerging in northern regions during May when temperatures reach 12–15°C (Burgess 1977). When temperatures are too low for flight (8–10°C), adults walk into fields and feed on the leaves and stems of brassicaceous plants before moving onto crops (Ulmer & Dosdall 2006). Damage to the cotyledons and first true leaves delays plant development, causing unevenness in height and maturity as well as reducing crop seed yields (Bodnaryk & Lamb 1991; Tansey et al. 2009). The effect of the feeding activity varies with the part of the plant fed on, plant development and the intensity of the attack. Although adult beetles can continue to cause some harm into the growing season, once plants are beyond the seedling stage, they are much less vulnerable to feeding damage (Gavloski & Lamb 2000) and, at the three- to four-leaf stage, plants are generally established enough to outgrow flea beetle injury (Sultani 2011). In northern regions, these pests have one generation per year and young adults...
of the next (summer) generation do not cause economically significant losses (Hiiesaar et al. 2006, 2009). The importance of flea beetles as pests is aggravated by the fact that several species also vector plant pathogens (Dillard et al. 1998).

Current control options for flea beetles consist primarily of seed dressing and the foliage application of broad spectrum insecticides which may create environmental as well as health hazards. Further, since pesticides are not persistent, reinvasion of the host plants after spraying can be rapid and even repeated treatment can fail to give adequate control (Howard & Parker 2000; Hiiesaar et al. 2006). These factors have led to increasing interest in non-chemical, less harmful ways of managing these pests.

Behavioural manipulation of insect pests has potential to be ecologically sustainable and economically viable. Plant chemistry influences the behaviour of phytophagous insects, but host selection is based on a combination of chemical, physical and environmental characteristics of plants (Soroka & Elliott 2011). The flea beetles of cruciferous plants are attracted to degradation products of glucosinolates, such as isothiocyanates and nitriles as well as to non-specific volatiles released from plants (Bartlet et al. 1993, 1997; Cook et al. 2007; Hopkins et al. 2009). Species of Brassicaceae and cultivars within species differ in their attractiveness or susceptibility to flea beetles (Bodnaryk & Lamb 1991; Palaniswamy et al. 1992; Ulmer & Dosdall 2006). Such differences may be attributed to poor synchrony between the phenology of flea beetles and host plants (Valantin-Morison et al. 2006), chemical composition of the host plants (Björkman et al. 2011) and to different microhabitat preferences among flea beetle species (Hicks & Tavanainen 1974). One non-chemical pest management strategy is the diversification of agricultural fields by establishing polycultures that include two or more crop varieties or species of different attractiveness to flea beetles within the same field (Altieri & Nicholls 2004). Kareiva (1985) reported that adult flea beetles move further when they encounter no acceptable plants in a polyculture. After that, they may spend time searching on the ‘wrong plant’, or after several encounters with unsuitable plants, leave the area in search of a more resource-rich habitat (Hooks & Johnson 2003). Another promising non-chemical technique for flea beetle management of crucifers is trap cropping (Trdan et al. 2005; Bohinc & Trdan 2012; Veromann et al. 2012), which is based on the principle that the pest prefers a certain plant species, cultivar or crop of a certain age and that the attractant plants lure the pest insects away from cash crops thereby limiting pest damage to them (Hokkanen 1991).

Species composition of flea beetles damaging cruciferous plants varies by region. For example, in North America, the most damaging pests of Brassicaceae are Phyllotreta cruciferae (Goeze) (crucifer flea beetle) and Phyllotreta striolata (=vittata) (F.) (wavy striped flea beetle; Soroka et al. 2005; Dosdall & Mason 2010), whereas in Central and Southern Europe, the prevalent species of flea beetles are Phyllotreta nemorum L. (striped flea beetle) and Phyllotreta undulata Kutschera (Redtenbacher) (small striped flea beetle) (Trdan et al. 2005). Phyllotreta armoracae Koch (horseradish flea beetle), Ph. cruciferae and Ph. undulata have been reported as the main flea beetle species on cabbage in Slovenia (Brelih et al. 2003). Determining the dominant flea beetle species in a specific locality is therefore important in selecting effective trap crops.

The aim of this study was to identify the species complex and abundance of the flea beetles associated with eight cruciferous oilseed crops: Brassica juncea (L.) Czern. (Indian mustard), Brassica napus L. var. oleifera subvar. annua (spring oilseed rape), Brassica nigra (L.) Koch (black mustard), Brassica rapa L. var. oleifera subvar. annua (spring turnip rape), Camelina sativa (L.) Crantz (false flax, camelina), Eruc a sativa Mill. (rucola), Raphan us sativus L. spp. oleifera (DC) Metzg. (oilseed radish) and Sinapis alba L. (white mustard), and to compare their relative attractiveness to flea beetles and thereby to determine their potential for use within a trap crop system for spring oilseed rape.

Materials and methods

Study area and experimental design

A two-year (2012 and 2013) field experiment was carried out at the Estonian University of Life Sciences (EULS) in Tartu, Estonia (58°21′N, 26°39′E). The plants were grown in a randomised complete block design with three replicates of each following species: B. juncea (cv. ‘Jadrijonaja’), B. napus (cv. ‘Mascot’), B. nigra, B. rapa (cv. ‘Largo’), C. sativa (cv. ‘Ligena’), E. sativa (cv. ‘Poker’), R. sativus (cv. ‘Bille’), and S. alba (cv. ‘Branco’). Seeds of plants collected from the experimental plots in the autumn of the previous year (2011 and 2012) were used. In study years (2012 and 2013), each plot was 1 × 5 m, with four rows per plot and a 1-m wide buffer zone of bare soil around each plot to minimise inter-plot interactions; the experimental field was surrounded by grassland. Plots were sown concurrently on 15 May 2012 and 14 May 2013, at 250 seeds per m². Test plant management was uniform in all plots; no pesticides or fertilisers were used.
Data collection

Plant growth stages (GSs, Table 1) were recorded every sampling day using the decimal code system of Lancashire et al. (1991). Data collection started at the time of oilseed test plants emergence (GS 9, cotyledons emerge through soil surface). Flea beetle abundance was assessed at weekly intervals for four to six consecutive weeks (until GS 30–39, stem elongation) by sampling with an aspirator, a simple mouth-sucking apparatus consisting of a glass jar and two plastic tubes (Burgess 1977; McLeod et al. 2011). Beetles were collected into separate vials from the central two rows (2 × 5 m) of each test plot. The flea beetles were collected early in the morning, when they were relatively inactive. Care was taken not to move the shadow of the sampler over perched flea beetles to avoid eliciting their jumping escape response. Vials were frozen and flea beetles later counted and identified using an Olympus SZ-CTV stereo microscope (Olympus Optical Co. Ltd, Japan). For identification to species, the keys of Haberman (1962) and Konstantinov et al. (2011) were used and verified by comparing with the reference collection of EULS.

Data analysis

Differences in the abundance of flea beetle species between years were analysed with one-way analysis of variance (ANOVA) and Fisher’s LSD post hoc tests ($\alpha = 0.05$). The same tests were applied to determine the effect of years, dates and plant species on the numbers of flea beetles. Two-way ANOVA was used to compare the proportions of Phyllotreta species between years and plant species. For this analysis, only four prevalent flea beetle species – Ph. undulata, Ph. nemorum, Ph. vittata and Ph. nigripes (turnip flea beetle) – were considered. Factors such as ‘year’ and ‘plant species’ were treated as fixed categorical variables. Multiple comparisons were done using the Fisher’s LSD post hoc tests. All analyses were carried out using STATISTICA 12 (StatSoft, Inc.).

Results

Weather conditions and GSs of the test plants

Daily mean temperatures in the region for May and June 2012 and 2013 are shown in Figure 1. Weather in May 2012 was similar to the long-term average (11.1°C), but June was about 3°C cooler (13.3°C), with 10 nights below 0°C on the soil surface. Growth and development of the test plants were delayed and most did not sprout until late June.

Early spring 2013 was cool and snow cover persisted into late April, but from 8 May temperatures exceeded the long-term average by 4°C with maximum temperatures reaching 25–27°C on several days. Warm weather continued into June (monthly average 17.7°C, i.e. 3°C above normal) with temperatures above 25°C for more than 10 days. The test plants grew and developed notably faster in 2013 than in 2012 (Table 1).

Table 1. Growth stage (GS) of cruciferous test plants on each sampling date in 2012 and 2013.

<table>
<thead>
<tr>
<th>Plant species</th>
<th>Year</th>
<th>Sampling schedule</th>
<th>GS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2012 2013</td>
<td>24 May 23 May</td>
</tr>
<tr>
<td>Camelina sativa</td>
<td>2012</td>
<td>0</td>
<td>9–11</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td>8–9</td>
<td>12–14</td>
</tr>
<tr>
<td>Raphanus sativus</td>
<td>2012</td>
<td>9–10</td>
<td>9–12</td>
</tr>
</tbody>
</table>

Flea beetle diversity

A total of 3957 flea beetles were caught from 24 May to 26 June in 2012 and 1560 from 23 May to 26 June in 2013. The years 2012 and 2013 were contrasting and the flea beetle abundance varied significantly (ANOVA: $F_{1,4} = 145.2, P < 0.001$).

Adults of six species of flea beetles were found on the oilseed crops, identified as *Phyllotreta atra* (cabbage flea beetle), *Phyllotreta nemorum*, *Phyllotreta nigripes*, *Phyllotreta undulata*, *Phyllotreta vittata* (=striolata) (all of Fam. Phyllotreta) and *Chaetocnema concinna* (Marsh) (beet flea beetle) (Chaetocnema). Differences between the flea beetle species’ numbers were statistically significant (ANOVA, 2012: $F_{5;12} = 162.8, P < 0.001$, 2013: $F_{2;8} = 279.6, P < 0.001$). *Ph. undulata* was by far the most abundant in both 2012 and 2013 (LSD test, all $P$ values $< 0.05$; Table 2). In 2012, mean numbers of *Ph. nemorum*, *Ph. nigripes* and *Ph. vittata* were similar with no significant difference between them (LSD test, $P > 0.05$). Numbers of *C. concinna* and *Ph. atra* were low in 2012 and differed significantly from those of all other species (LSD test, all $P$ values < 0.05), but not from each other (LSD test, $P = 0.8$). In 2013, *Ph. undulata* was again the most commonly found species, its numbers exceeding that of every other flea beetle species (LSD test, all $P$ values < 0.05). Numbers of *Ph. nigripes* and *Ph. vittata* were smaller and did not differ significantly (LSD test, $P = 0.9$). Few *Ph. nemorum* were found, significantly fewer than all other flea beetle species that year (LSD test, all values $P < 0.05$). *Ph. atra* and *C. concinna* were not found in 2013.

Timing of species abundance

Time of emergence and activity varied with species. In 2012, *C. concinna*, *Ph. nemorum*, *Ph. nigripes*, *Ph. undulata* and *Ph. vittata* were detected as most oilseed test plants began sprouting (GS 9–11, 24 May 2012, Table 1), but no *Ph. atra* were then seen. *Ph. undulata* occurred in large numbers throughout the observation periods of both 2012 (LSD test, all $P$ values $< 0.05$, Figure 2A) and 2013 (Figure 2B). *Ph. nemorum* appeared only at the beginning of the observation period in both 2012 and 2013. In 2012, numbers declined gradually, whereas in 2013, they were present only in early samples. *Ph. vittata* was prevalent in the first half of the observation period in both years; later, their numbers fell to remain low until the end of the season. *Ph. nigripes* was found in low numbers in all samples in both years. *C. concinna* was present at a low density only in 2012 and was missing in 2013. *Ph. atra* was the last species to emerge at the beginning of June.

### Table 2. Mean abundance (±SE) of species of flea beetles on the cruciferous test plants in 2012 and 2013.

<table>
<thead>
<tr>
<th>Flea beetle species</th>
<th>2012</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Chaetocnema concinna</em></td>
<td>17.3 ± 3.1*</td>
<td>0.0 ± 0.0*</td>
</tr>
<tr>
<td><em>Phyllotreta atra</em></td>
<td>22.6 ± 6.6*</td>
<td>0.0 ± 0.0*</td>
</tr>
<tr>
<td><em>Phyllotreta nemorum</em></td>
<td>151.0 ± 6.8b</td>
<td>13.0 ± 0.6a</td>
</tr>
<tr>
<td><em>Phyllotreta nigripes</em></td>
<td>182.6 ± 9.0b</td>
<td>73.0 ± 7.0b</td>
</tr>
<tr>
<td><em>Phyllotreta undulata</em></td>
<td>814.3 ± 55.9c</td>
<td>330.0 ± 2.2c</td>
</tr>
<tr>
<td><em>Phyllotreta vittata</em></td>
<td>128.3 ± 2.8b</td>
<td>74.0 ± 9.3b</td>
</tr>
<tr>
<td>$F$</td>
<td>162.8</td>
<td>279.6</td>
</tr>
<tr>
<td>d.f.</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>$P$</td>
<td>0.0001</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Flea beetle data are shown as mean ± standard error. Means within columns followed by different letters are significantly different at $P < 0.05$ (ANOVA, LSD test).

*The analysis gave no data to compare the mean of *Ph. atra* and *C. concinna*. 

Figure 1. Average daily temperatures in May and June 2012 and 2013 (Meteos Compact Rõhu, Estonia).

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in 2012 and in low numbers; none were found in 2013.

**Host plant infestation level**

Plant species had a significant influence on flea beetle abundance (ANOVA, in 2012: $F_{7;16} = 23.2$, $P < 0.001$; in 2013: $F_{7;16} = 6.1$, $P = 0.001$; and averaged over two years: $F_{7;16} = 20.6$; $p < 0.001$).

Adult flea beetles preferred *B. juncea*, *B. nigra*, *E. sativa* and *R. sativus* over oilseed rape *B. napus* (Figure 3). In 2012, the highest number was recorded on *E. sativa*, significantly greater (LSD test) than on *B. rapa* ($P = 0.001$), *S. alba* ($P < 0.001$), *B. napus* ($P < 0.001$), *B. nigra* ($P = 0.01$) and *C. sativa* ($P < 0.001$). No differences were found between beetle abundance on *E. sativa* and *B. juncea* ($P = 0.4$) or *E. sativa* and *R. sativus* ($P = 0.17$). Relatively few individuals were found on oilseed rape (*B. napus*). Moreover, the infestation level on *B. napus*, which was the main cash crop in the study, was significantly lower than on *B. nigra* ($P = 0.02$), *E. sativa* ($P < 0.001$), *B. juncea* ($P < 0.001$) or *R. sativus* ($P = 0.001$). No significant difference was found in numbers on *B. napus* and *B. rapa* ($P = 0.15$) or *B. napus* and *S. alba* ($P = 0.5$). In 2013, the highest number was again recorded on *E. sativa*, significantly more than on *B. rapa* ($P < 0.001$), *B. napus* ($P = 0.009$), *R. sativus* ($P = 0.007$) and *C. sativa* ($P < 0.001$). No differences were found between numbers on *E. sativa* and *S. alba* ($P = 0.09$), *E. sativa* and *B. nigra* ($P = 0.62$), and *E. sativa* and *B. juncea* ($P = 0.23$). Oilseed rape resulted in low numbers of flea beetles also this year, although...
there was no significant difference between B. rapa ($P = 0.22$), S. alba ($P = 0.26$), B. juncea ($P = 0.1$), R. sativus ($P = 0.92$) or C. sativa ($P = 0.06$).

During the two-year study, the highest number of flea beetles was found on E. sativa, significantly more (LSD test) than on B. napus, B. rapa, S. alba, R. sativus, B. nigra or C. sativa (all $P$ values < 0.05). Flea beetle abundance on B. napus was significantly lower than on B. nigra ($P = 0.007$), E. sativa ($P < 0.001$), B. juncea ($P < 0.001$) and R. sativus ($P = 0.01$). There was no difference in abundance on B. napus, B. rapa ($P = 0.5$) and S. alba ($P = 0.29$). Abundance was lowest on C. sativa, significantly less than on the other plant species (LSD test, all $P$ values < 0.05).

Species composition of flea beetles on plants

Concerning the percentage distribution of the flea beetle in crops, a great portion of the catch was Ph. undulata, irrespective of the crop, with the exception of C. camelina, on which only 11.2% of the total number sampled at a given moment was this species. Ph. undulata was the dominant species by 56.8% of the total catch of beetles over two years; other species occurred only in smaller proportions: Ph. nigripes (17.8%), Ph. vittata (10.3%), Ph. nemorum (9.8%), Ph. atra (2.9%) and C. concinna (2.4%).

When testing the effect of host plant on the relative infestation rate of the four most prevalent flea beetle species Ph. undulata, Ph. nemorum, Ph. vittata and Ph. nigripes by a two-way ANOVA, plant host species was not a significant factor in either year or averaged over the two years (two-way ANOVA in 2012: $F_{3,7} = 0.07$, $P = 0.9$; in 2013: $F_{3,7} = 0.003$, $P = 1$; and pooling the two years: $F_{3,7} = 0.02$, $P = 0.9$). On the other hand, flea beetle species composition was a significant factor (two-way ANOVA in 2012: $F_{3,7} = 22.1$, $P = 0.000$; in 2013: $F_{3,7} = 15.7$, $P < 0.001$ and pooling the two years: $F_{3,7} = 19.5$, $P < 0.001$).

The abundance and composition of the Phyllotreta species pooling the two years complex varied to some extent between host plants (Figure 4). Ph. undulata was a dominant species constituting over 60% of the total collected from the eight plant species, whereas other flea beetles occurred only in smaller proportions. Species composition in false flax C. sativa differed, however, as Ph. nigripes was a dominant species with significantly higher prevalence when compared to the numbers of other species in this plant (Figure 4). Ph. vittata was found present approximately at the same level on B. napus, B. juncea, B. rapa and B. nigra, fluctuating between 12.4% and 15.6%. Somewhat lower were the percentages on C. sativa, R. sativus, E. sativa and S. alba, at 9.5–10.8%. Ph. nemorum was not found on C. sativa. Other test plants were infested by this species at 3.9–10.35% prevalence.

Discussion

We recorded six species of Alticinae flea beetles on our cruciferous test plants: C. concinna, Ph. atra, Ph. nemorum, Ph. nigripes, Ph. undulata and Ph. vittata (striolata); this is similar to the species composition reported on cruciferous plants in Estonia (Hiiesaar et al. 2003, 2004; Liblikas et al. 2003), Sweden
Ph. undulata attacked our study plants in both study years and in highest abundance. This transpalaearctic species is common in several countries and has been recorded as the dominant species in earlier studies in Estonia (Hiiesaar et al. 2003; Liblikas et al. 2003) where it also prevails on Brassica vegetables: B. napus var. napobrassica (L.) Rchb. (rutabaga or swede), B. oleracea L. var. capitata f. alba (white cabbage), B. rapa rapa L. (white turnip) and Raphanus sativus var. sativus Pers. (radish). Ph. undulata abundance on cruciferous crops in Estonia indicates that it is well adapted to local conditions. Adult flea beetles overwinter near the soil surface under debris, where minimum temperatures are usually higher than their cold hardiness. Consequently, overwintering mortality due to low temperature may be limited only to extremely severe snowless winters (Hiiesaar et al. 2009). The population growth is probably supported also by the exponential increase in oilseed rape cultivation (Veromann et al. 2012; Kaasik, Kovacs, Toome et al. 2014), which provides this oligophagous pest species with good conditions for nourishment and reproduction.

Ph. nemorum was rather low in abundance on our test plants. This oligophagous beetle attacks a number of cruciferous weeds, including Lepidium draba L. (whitetop), Raphanus raphanistrum L. (wild radish), Sinapis arvensis L. (wild mustard), but also R. sativus L. (cultivated radish) and Barbarea vulgaris ss. arcuata (Opiz.) Simkovics (rocket cress) (Barel et al. 2012), and Ekbom (2010) found it more often on cruciferous weeds, than on cruciferous crops. Nevertheless, it has been reported as a significant pest of vegetable Brassicas (Alford et al. 2003) and oilseed rape (Veromann et al. 2006; MOCA Study 2004, Latvia). To migrate, Ph. nemorum usually walks or jumps, and although it can also fly, it does so infrequently so its migration between sites may be limited (De Jong & Nielsen 2002). One of the reasons why this species occurred in low numbers in our experiment could have been the plentiful distribution of spring flowering cruciferous weeds in the vicinity of the experimental field [Barbarea spp, Capsella bursa-pastoris L. (Sheperd’s Purse) R. raphanistrum, S. arvensis, etc.]. This species is the only one of those recorded whose females lay eggs into leaf epidermises and whose adults and larvae can both feed on the leaves of the same plant species (De Jong et al. 2001). Thus, once the food plant has been colonised, the adults do not have to migrate for oviposition sites on alternative hosts (in our case, the crops germinating later in the season). Ph. nigripes was detected regularly in small numbers in both study years. Hiiesaar et al. (2003) similarly found that it occurred in low numbers on spring oilseed rape cv. ‘Mascot’ constituting only about 10% of the total catch. Thus, this species is common but not abundant on cruciferous oilseed crops in Estonia. Being non-selective, Ph nigripes feeds on several cultivated and wild brassicas and, in their absence, on deciduous trees and bushes (Hiiesaar et al. 2003). Toshova et al. (2009) also found that this species was not abundant on cruciferous vegetable crops, but damaged Beta vulgaris L. (beet), Rosa damascena Mill (Damask rose) and Solanum lycopersicum L. (tomatoes). We conclude that the polyphagy of adults is the main reason why spring-sown cruciferous crops are not a vital resource for this species.
Ph. vittata appeared most abundant in early samples, becoming scarcer later on. This concurs with other reports, indicating that the species is one of the earliest flea beetles on crucifers in spring (Hiiesaar et al. 2003; Tansey et al. 2009). As a cosmopolitan species, it could be a serious pest in many locations and primarily a pest of economically important Brassica crops (Soroka et al. 2005). Nevertheless, their prevalence was low in our experiment; hence they cannot be considered a serious oilseed crop pest. Adults became more active when daily average temperature exceeded 8–10°C, and when daily temperature exceeded 26°C, their activity dropped considerably (Shi-Tong et al. 2008). Thus, the species differs from the rest of the species complex by optimum temperatures. The long period of abnormally high temperatures in May–June 2013 may have been one factor causing the disappearance of Ph. vittata from the test plots. Apart from that, the species, being shade-tolerant, may have occurred lower down in the canopy and under leaves, making collection by aspirator more difficult (Tahvanainen 1972; Burgess & Spurr 1984).

Although, C. concinna and Ph. atra species have a broad host range, including plants in the family Brassicaceae, and can sometimes cause significant economic damage to a variety of cultivated crops (Cagán et al. 2000), these species were scarce in our experiment. Hiiesaar et al. (2004) encountered C. concinna, but established that it did not damage rape seed plants but was found on several species of Brassica weeds growing in the same area.

The difference in abundance of flea beetles between the seasons could be caused by several factors, for example, differences in the rate of plant growth triggered by weather conditions, direct effects of temperature, humidity, plant species, cultivar, variety, etc. since each of these factors may cause changes in plant quality and thus also attractiveness. Furthermore, synchrony between the phenology of the insect herbivores and that of the host plant has a major impact on the population densities of many leaf-feeding insects (van Asch & Visser 2007). In our study years, weather conditions were very different; this was reflected in the numbers of flea beetles sampled, which varied considerably between the two seasons. The spring emergence of flea beetles in 2012 was delayed due to the cool, wet April and May and flea beetles remained relatively inactive and slow to emerge; also plant growth and development remained abnormally slow. Although the cool, damp weather halted flea beetle activity, they tend to survive in spite of the reduced activity level. Backward plants provided the flea beetles with a suitable growth phase for an extended period of time. By contrast, in 2013, there was an extremely warm May, when flea beetles became active and started leaving their overwintering sites to seek host plants simultaneously. The acceptable plants available to flea beetles dispersing from overwintering sites were cruciferous weeds (our personal data), as summer oilseed crops were not yet available. Suzuki (1986) found that female chrysomelid beetles often lose their ability to disperse once the period of ovarian development has been completed causing populations to remain fairly localised and to specialise on plant resources in the immediate area. Most of the study plant species germinated and developed unusually fast due to exceptionally warm weather in our experiment in 2013, exhibiting the GS acceptable to the flea beetles for a few weeks only. On common brassica oilseed plants the first leaves to emerge on these plants are very attractive to flea beetles, but as they mature, the leaves become waxier and it is difficult for the beetles to grasp and feed on them (Trdan et al. 2009); this is when the vast majority abandon the food plants in sprouting phase and leaves for other, more attractive food plants. The flea beetles had migrated from most of our study plant species and resettled on white cabbage in the vicinity already by the beginning of June 2013. Asynchrony of flea beetle phenology with growth of oilseed cruciferous test plants and the migration of flea beetles from these crops to newly planted white cabbage may be factors determining abundance of summer generation flea beetles. Moreover, Gao et al. (2000, 2005) determined that low temperatures in winter and high temperatures in the warm season had a negative effect on populations of flea beetles. Thus, we can conclude that the extremely different weather conditions and speed of growth of the experimental plants were important factors determining the intensity of flea beetles in both years.

Our results demonstrated the ability of flea beetle species to discriminate between the studied host plants as shown by other authors (Hiiesaar et al. 2003, 2006; Bohinc & Trdan 2012, 2013). Although the development of B. juncea, B. nigra and B. rapa was rather synchronous, flea beetles were not equally abundant on them, indicating their differential attractiveness even in the same GS at the same time. The beetles preferred B. juncea and B. nigra over B. rapa, supporting earlier literature data. B. juncea has been previously cited as an effective trap plant for flea beetle, Meligethes aeneus Fab. (pollen beetle), Ceutorhynchus obstrictus (Marsham) (cabbage seedpod weevil; Kovács et al. 2013; Kaasik, Kovacs, Toome et al. 2014) and several lepidopteran pests of cole crops (Luther et al. 1996). Hicks and Tahvanainen (1974) established in a choice experiment with several cruciferous species that Ph. crucifera
favours *B. nigra*. Furthermore, *B. nigra* has been shown to be considerably more attractive than *B. napus* to overwintered pollen beetle adults for feeding as well as for oviposition (Veromann et al. 2012; Kaasik, Kovacs, Kaart et al. 2014). Attractiveness of oilseed rape and turnip rape have been compared by Palaniswamy et al. (1992) who found that *B. napus* and *B. rapa* were approximately equally susceptible to flea beetle attack. Even though white mustard *S. alba* emerges earlier and grows faster than oilseed rape, it did not attract more beetles. The susceptibility of *S. alba* to flea beetles is described by Bohinc and Trdan (2012). This plant can defend itself against an attack by harmful organisms in several ways: chemically by means of glucosinolates (Bodnaryk & Lamb 1991; Björkman et al. 2011; Bohinc et al. 2012) and physically by means of trichomes (Soroka et al. 2011). We found that flea beetles displayed a preference for *E. sativa* and *R. sativus*. One reason could be their longer growth periods. These results concur with both Soroka and Grenkov (2013), who found that *E. sativa* was an excellent flea beetle host as well as with Bohinc and Trdan (2012), who showed that oilseed radish *R. sativus* was very attractive to flea beetles. We observed flea beetles on *C. sativa*, but they were less abundant and of different species composition than on the other oilseed test plants studied. Our finding that *Camelina* is not a host for cruciferous flea beetles concurs with investigations by Pachagounder et al. (1998) and Henderson et al. (2004). There have been several attempts to explain the lack of attractiveness of *Camelina* to flea beetles. Kogan and Ortman (1978) found that antixenotic resistance (when plant metabolites are deterrent) which disrupts normal host selection behaviour is based on plant characteristics that prevent insect colonisation of a plant. High levels of antixenotic resistance for flea beetles have been found in *C. sativa* (Pachagounder et al. 1998). Onyilagha et al. (2012) discovered that its leaves and cotyledons contain large amounts of quercetin, which is considered a chemical defence against flea beetles and camelina had very few pests. Such plant species that are unacceptable or less acceptable to flea beetles could be of value in developing alternative methods for their control, such as for use as repellent intercrops in oilseed rape fields.

In our study, *B. juncea* and *B. nigra* developed faster and at GS they were more attractive to overwintered adult flea beetles than *B. napus* and therefore had potential as trap plants to protect spring rape. We also showed that *R. sativus* and *E. sativa*, despite their development rate being slower than the above-mentioned species, were also attractive to flea beetles. Thus, further experiments with a complex of attractive early season and late-season plant species should be undertaken (multiple trap crops). These mixtures should occupy flea beetles while the primary crop is emerging and getting established. Initially, flea beetles are attracted to *B. juncea* and *B. nigra* but, when senescence causes them to be less attractive, flea beetles will migrate to *E. sativa* and *R. sativus*. Such a combined trap may be preconditioned to work effectively over an extended period hence cancelling out the migration of flea beetles to oilseed rape, simultaneously reducing the damage flea beetles cause to transplanted cruciferous vegetable crops. Careful monitoring of the trap crops and routine pest removal are essential for this strategy. These plants and plant combinations justify more detailed testing in field environments and a good knowledge of insect life cycles and migration patterns.

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