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Natural regulation of *Delia radicum* in organic cabbage production

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ABSTRACT

In a field experiment, we evaluated effects of three different organic white cabbage-cropping systems (O1, O2, O3) on the cabbage root fly, *Delia radicum*, and its egg predators and pupal parasitoids over 3 years. The three systems all complied with regulations for organic production, but varied in external nutrient input and N-recycling, and were compared to a conventionally farmed control. One organic system (O3) included an intercropped strip of green manure between crop rows. Oviposition by *D. radicum* was generally not reduced in organic cropping systems. However, higher pupae/egg ratios were observed in the conventional compared to all organic systems, indicating that immature survival from oviposition to pupation was reduced under all the three organic farming practices. In organic system O2 most small coleopteran predators were recorded, but predation on fly eggs was not significantly higher in organic treatments. Pupal parasitization rates ranged from 26.5% to 59.5%, but no significant differences among farming systems were found. Although reduced *D. radicum* survival could not be attributed solely to natural enemies, the results indicated that organic farming practices in general contribute to the suppression of belowground pests in cabbage production.

1. Introduction

The cabbage root fly *Delia radicum* (L.) (Diptera: Anthomyiidae) is a major belowground pest in brassicaceous vegetables in northern Europe (Finch and Collier, 2000b; Hooks and Johnson, 2003) and management practices must be implemented to control this pest (Zehnder et al., 2007). Intercropping with, e.g. clover has proved to be an efficient pest management strategy reducing oviposition by *D. radicum* (Finch and Collier, 2000a,b; Hooks and Johnson, 2003). Eggs of *D. radicum* are preyed upon by various small ground dwelling predatory beetles including carabids and staphylinids (Wishart et al., 1956; Hughes, 1959; Finch, 1996; Prasad and Snyder, 2004). The predation on eggs contributes to biological control of root flies (e.g. Finch, 1996; Bjorkman et al., 2010). Moreover, larvae of *D. radicum* are attacked by the parasitoids *Trybliographa rapae* (Westwood) (Hymenoptera: Figitidae) and *Aleochara bilineata* (Gyll.) (Coleoptera: Staphylinidae) (Finch and Skinner, 1980; Jones et al., 1993). The two parasitoid species usually co-occur, collectively contributing to the regulation of *D. radicum* (Bonsall et al., 2004; Hummel et al., 2010).

Organic farming generally benefits natural enemy performance and abundance (Birkhofer et al., 2008; Garratt et al., 2011) and enhances characteristics of natural enemy communities that may result in improved biological pest control compared to conventional farming (Crowder et al., 2010). However, increasing diversity of natural enemies through, e.g. habitat management (Landis et al., 2000) may not result in enhanced biological pest control due to increased niche overlap and/or intraguild predation (Straub et al., 2008; Prasad and Snyder, 2006).

Organic fertilizer methods have profound effects on aboveground pests (Eigenbrode and Pimentel, 1988; Alyokhin et al., 2005; Birkhofer et al., 2008; Hsu et al., 2009; Garratt et al., 2010; Staley et al., 2010) with manures showing consistent negative effects while composts have positive effects (Garratt et al., 2011). However, effects on root feeding herbivores have received limited attention. Furthermore, effects of manure applied as organic fertilizer on natural enemies are poorly investigated (Garratt et al., 2011). Organic farmers can reduce the application of animal manures (e.g. slurry) by combining with green manures prior to crop planting. As intercropping can be implemented as a pest management tool for *D. radicum* (Finch and Collier, 2000b), conserving strips of green manure between the crops could provide the benefits of intercropping on *D. radicum* oviposition as well as providing habitat refuges for predators (Landis et al., 2000), also between seasons until the time of cabbage establishment.

In the present study we wished to evaluate the effects of organic farming practices of white cabbage compared to a conventional

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Table 1
Plant cover, soil management, fertilization and plant protection in the four farming systems with white cabbage: C, conventional system (control); O1, organic system with high import of slurry; O2 and O3, organic system with low import of slurry and green manure. In O3, strips of green manure were left in between crop rows. Field management followed approximately similar schedules each year.

Treatment		Farming system			
		C	O1	O2	O3
Undersowing		No	No	Lucerne/red clover	Bird's foot trefoil/ryegrass
Soil	Ploughing (green manure incorporation)	November	November	March	
	Rotovation (incorporation of green manure in rows)[a]				November
	Rotovation repeated plus loosening of soil				April/May
Establishment	Sowing[b]	April	April	April	April
	Transplanting cabbage to the field plots	May	May	May	May
Fertilizer	NPK (21%N, 3%P, 10%K)	310 kg N ha^{-1} [c]			
	Pig slurry		April (225 kg N ha^{-1})	April (135 kg N ha^{-1})	April (135 kg N ha^{-1})
Pest control	Azoxystrobin (synthetic fungicide, Amistar®)	750 g ha^{-1} [d]			
	Bacillus thuringiensis var. *kurstaki*[e]	3–4 l ha^{-1} [f]	3–4 l ha^{-1} [f]	3–4 l ha^{-1} [f]	3–4 l ha^{-1} [f]
	Alpha-cypermethrin (synthetic insecticide, Fastac 50®)	20 g ha^{-1} (June 2007) 60 g ha^{-1} (2008–2009)[g]			
	Pirimicarb (synthetic insecticide, Pirimor G®)	250 g ha^{-1} [h]			
Harvest		October	October	October	October

[a] The green manure was sown across the whole area of the plot. By rotovation in November 1.3 m bands of the green manure was incorporated, leaving 0.3 m strips growing next to every second cabbage row.
[b] Cabbage was sown in small containers (speedlings) in greenhouse.
[c] The fertilization was split into three equal sized applications (May, June and July).
[d] Fungal control was carried out in 2008 only and the stated dosage was into split three applications; one in August and two in September.
[e] Trade name Dipel ES®.
[f] Split into three applications of 1 l ha^{-1} in July/August 2007 and four applications of 1 l ha^{-1} in August 2008 and 2009.
[g] Split into three applications (May, June and July).
[h] Pirimicarb was only applied in August 2007.

farming practice on: (i) oviposition of *D. radicum* in white cabbage; (ii) the relationship between oviposition and pupal production; (iii) predation rates on fly eggs; (iv) abundance of potential egg predators; and (v) parasitization rates by and relative species abundance of parasitoids in *D. radicum* puparia. We included three different organic farming systems, all of which complied with official requirements for being certified as "organic". In addition, a fourth system (control) was conventionally farmed. All four systems included the same crop rotation of main crops, but the three organic systems differed in reliance on external nutrient input and nutrient recycling from pure import of high amount of slurry to low slurry import combined with green manures. One of the organic practices included an intercropped strip of the green manure between crop rows.

2. Materials and methods

The experimental farming systems were located at a research farm in Årslev (10°27′E, 55°18′N), Denmark, and maintained as a field experiment over four seasons from 2006 to 2009. White cabbage (*Brassica oleracea* L. convar. *capitata* (L.) Alef. var. *alba* DC 'Impala') was grown as a part of an experimental rotation with other vegetables and cereals, and cabbage always followed winter rye (*Secale cereale* L.). Crops were grown using four different farming practices (see Table 1 and Thorup-Kristensen et al., 2012). One was a conventionally farmed system (C) with application of both synthetic fertilizer and chemical pesticides, and three were organic systems: (O1) dependent on high external input of organic fertilizer (slurry) and without undersowing green manure and no nutrient recycling; (O2) low external input of organic fertilizer (slurry), undersown green manure and nutrient cycling using catch crops; and (O3) low external input of organic fertilizer (slurry), green manure and catch crops as in O2, but with the difference that strips of the previous year's green manure were left in between the crop rows. In O2 a green manure mixture of lucerne (*Medicago sativa* L.) and red clover (*Trifolium pratense* L.) was established in the rye crop in spring and incorporated in late autumn before the cabbage crops, whereas in O3 the green manure consisted of a mixture of bird's foot trefoil (*Lotus corniculatus* L.) and ryegrass (*Lolium perenne* L.), to achieve a less aggressive competition from the strips of green manure when growing between the cabbage rows (Båth et al., 2008). This meant that in O3 two rows of cabbage alternated with one strip of green manure whereas the three other systems had three crop rows on the similar area. The crops were grown in experimental plots of 10 m × 12.5 m, and each plot was prepared with seven beds each planted with three crop rows. Each row contained 16 plants. All experimental plots in the complete crop rotation (eight plots, see Thorup-Kristensen et al., 2012) receiving each of the four farming practices measured 10 m × 130 m, and each of these were separated by 8 m to the neighbouring treatment. Permanent grass was established between treatments in mid May each year. Distances between individual plots planted with white cabbage in the four treatments varied from 8 to 80 m depending on year due to the rotation. The experimental treatments were replicated in three fields (blocks) within the same experimental farm separated by distances of 75–100 m.

Cabbage seeds were coated with a mixture of thiram/carbendazin/iprodione/metalaxyl-m in the conventional system. In all four systems, plants were grown from seeds in the greenhouse and transplanted to the field in mid May, thus avoiding the peak flight period of the first generation of *D. radicum*. Small white *Pieris rapae* (L.) (Lepidoptera: Pieridae) larvae were controlled with *Bacillus thuringiensis* (Bt) var. *kurstaki* (Dipel ES®) when needed in all cabbage plots in accordance with Danish regulation for organic farming. Weeds were controlled with mechanical weeding in the three organic systems until late July

when competition from the crop canopy was sufficient to prevent weed growth.

2.1. Fly oviposition

Oviposition of *D. radicum* first and second generation was assessed 2007–2009 on 12 plants per plot, i.e. plant no. 4, 7, 10 and 13 out of the 16 plants per row, in three rows of second, fourth and sixth bed, respectively. For the first generation, plants of the second row of each of the three beds were sampled while plants of the first row of each of the three beds were sampled for the second generation. Once a week, the top soil was sampled with a spoon to a depth of 1 cm and in a radius of 3 cm around the stem of each selected plant. The soil samples were placed in separate plastic cups, fitted with a lid and kept cool in a box. The samples were stored at 5 °C until eggs were counted. Counting was done by pouring small portions of the soil into a beaker with tap water. Eggs were removed from the water surface with a fine paint brush. When no more eggs were visible the water was stirred and emerging eggs were removed until no more appeared.

Oviposition of the first generation was monitored for 3 weeks after transplanting the plants in the rows in mid May. During the flight of the second generation soil was sampled once a week for 3–4 weeks. Flight of the second generation was estimated using the on-line temperature dependent forecasting model provided by PlanteInfo (www.planteinfo.dk), which is an information and decision support system used by Danish farmers and agricultural advisers. Generally, the second generation of *D. radicum* was monitored from mid July onwards.

2.2. Overwintering individuals

In late October or early November 2006–2009 cabbage root systems and surrounding soil were sampled few days after harvest to estimate the number of overwintering *D. radicum* pupae in the plots. In each plot 10–12 root systems were collected inside cylindrical soil cores (14 cm in diameter, 16 cm deep), which were placed individually in polyethylene bags. Roots were selected arbitrarily in the central part of each plot avoiding plants that had been sampled for eggs. The soil cores were kept at 5 °C for 2–3 months. Soil and root of each core was washed and sieved (mesh size 1 mm) and pupariae were collected. The puparia from each sample were placed on a nylon mesh (mesh size 1 mm) and kept moist in a beaker with perforated lid. The beakers were incubated at 20 °C in a climate cabinet and emerging insects were counted. These included *D. radicum* and the parasitoids *T. rapae* and *A. bilineata*. Unhatched puparia were dissected under a stereo microscope for inspection of contents.

2.3. Egg predation

Predation of fly eggs in the four systems was assessed in 2007 and 2008 using sentinel eggs placed in the experimental plots. Eggs from the house fly *Musca domestica* L. (Diptera: Muscidae) were used as surrogates for *D. radicum* eggs following Prasad and Snyder (2004, 2006). House fly eggs originated from a continuous rearing at the Danish Pest Infestation Laboratory, Aarhus University, Sorgenfri, Denmark. Eggs were harvested and immediately frozen at −20 °C and used for field experiments after 1–2 weeks. Sentinel egg units were prepared by placing ten eggs on a 1 cm × 1 cm card of moist compressed sphagnum pot fitted with a wooden toothpick. The cards were kept frozen overnight. In the experimental plots, an area of soil surface within 5 cm from a cabbage plant was smoothened and each card was placed eggs facing upwards by inserting the toothpick in the soil. Each card was covered with a thin layer of soil particles (0.2–0.3 cm deep). Six cards were placed in each plot in second, fourth and sixth bed of each plot by plants no. 5 and no. 11. Each card was fitted with a protecting roof made of a 6 cm semi-transparent plastic lid mounted on an 8 cm nail. In each plot, one to two controls were placed consisting of a card with fly eggs surrounded by a transparent plastic cylinder open at the top (diameter 9 cm) that was pressed 1–2 cm into the soil to exclude epigeal predators. The sentinel eggs were exposed in the plots for 24 h at one occasion in May and two occasions in July of each year. Each card and surrounding soil was removed and placed in an individual lidded cup and kept cool for transportation. The cups with soil were frozen until the remaining numbers of eggs were estimated. Only complete and undamaged eggs were scored as remaining eggs.

2.4. Activity-density of egg predators

During the exposure of sentinel eggs for predation activity-density of ground-dwelling predators was assessed by pitfall trapping in the plots. Transparent plastic cups (diameter 9 cm) were filled with 100 ml of a mixture of 1:1 ethylene glycol and tap water. Two traps were placed in third, fifth and seventh bed between plant no. 4 and 5, and no. 12 and 13, respectively, yielding six traps per plot. Traps were placed in the plots at the same day as sentinel eggs were exposed. The pitfall traps were left for 3 days and then removed, lidded and transported to the laboratory where they were placed at 5 °C until the arthropods were sorted and placed in 70% ethanol for storage. Carabid beetles were identified to species level and staphylinids were identified to subfamilies and sorted in size categories. For each pitfall trap small carabids belonging to *Bembidion lampros* (Herbst), *Bembidion tetracolum* Say, *Bembidion quadrimaculatum* (L.), *Bembidion obtusum* Serville, *Trechus quadristriatus* (Schrank), *T. discus* (F.) and *T. micros* (Herbst) were collectively grouped as "small beetles" together with all staphylinids of subfamily Aleocharinae measuring 8 mm or less in length following Prasad and Snyder (2004, 2006).

2.5. Data analyses

The number (+1) of eggs laid and overwintering puparia per plant were $\log_e$-transformed and analyzed by mixed models in PROC MIXED in SAS with random effects of experimental field and experimental plot adjusting degrees of freedom by Satterthwaite formulae. For oviposition data, collection plant was also included as random factor. Fixed effects were farming system and week of collection. Mixed models were also applied to the data from individual pitfall trappings of small beetles after $\log_e$-transformation as well as for selected carabid species.

Proportions of overwintering puparia harbouring parasitoids and proportions of fly eggs recovered in egg predation experiments were analyzed by logistic regression models with random effects of field and experimental plot using PROC GLIMMIX in SAS testing for fixed effect of farming system for parasitoids, and of farming system and experimental week for egg predation.

Egg survival success until pupation in 2007–2009 was estimated as the number of overwintering puparia in each plot divided by the number of eggs laid in the same plot during second generation oviposition. These proportions were analyzed by logistic regression models with random effects of field using PROC GLIMMIX in SAS testing for fixed effect of farming system, year and farming system × year.

Significant effects ($p < 0.05$) were tested by lsmeans and adjusted by the Tukey–Kramer adjustment to identify pair-wise differences.

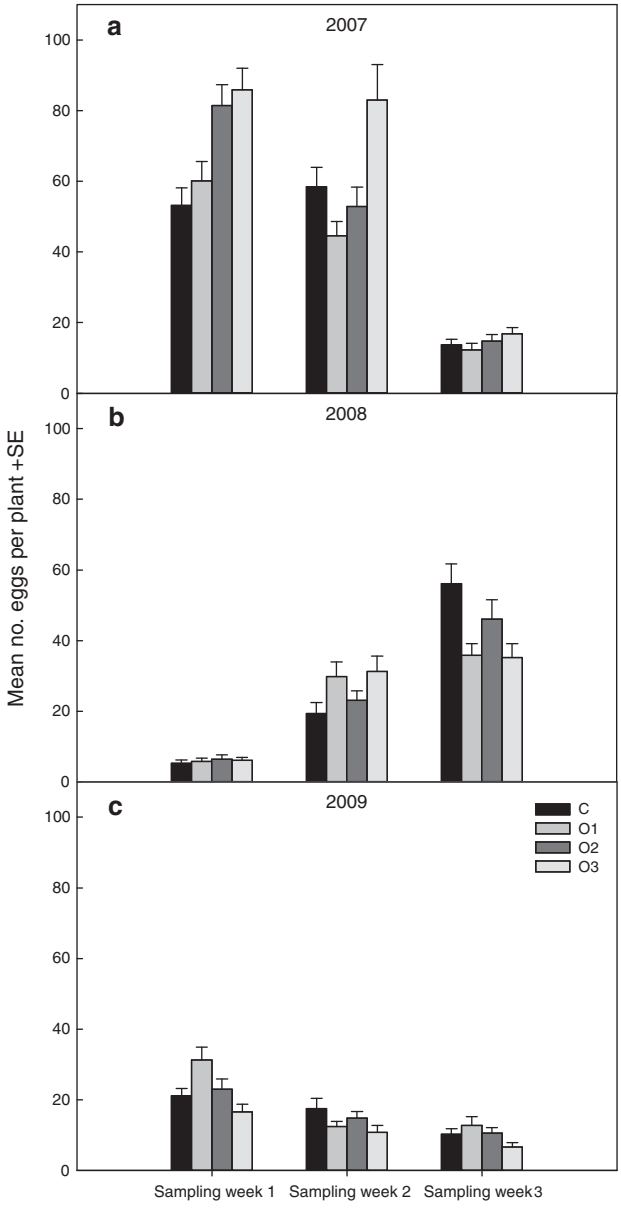

Fig. 1. Mean number (+S.E.) of second generation *D. radicum* eggs per plant per sampling week in 2007 (a), 2008 (b) and 2009 (c) in four farming systems (abbreviations cf. Table 1).

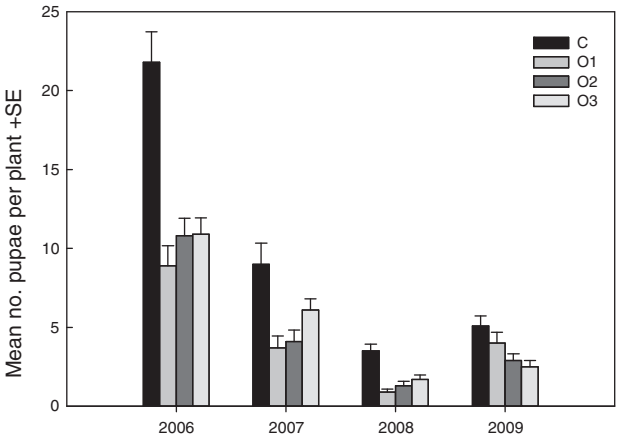

Fig. 2. Mean number (+S.E.) of *D. radicum* puparia per plant 2006–2009 in four farming systems (abbreviations cf. Table 1).

3. Results

Oviposition by first generation *D. radicum* varied over the 3 weeks of sampling in 2007 with highest levels in system C during the first week (10.3 eggs/plant) and in systems O2 and O3 in the third week (10.8 eggs/plant) with a significant farming system and week interaction ($F_{6,323} = 9.66$; $p < 0.0001$). For second generation oviposition in 2007 significant effects of farming system ($F_{3,99.2} = 7.06$; $p = 0.0002$) and sampling week ($F_{2,336} = 305.05$; $p < 0.0001$) were found (Fig. 1a). Oviposition was significantly higher in O3 compared to C and O1 (Tukey–Kramer adjustment: $p < 0.01$). Egg laying activity decreased from first to second to third week (Tukey–Kramer adjustment: $p < 0.005$).

In 2008, first generation oviposition continued through the 3 weeks of sampling (3.5–8.5 eggs/plant/week) with an overall farming system and week interaction ($F_{6,332} = 3.95$; $p = 0.0008$). There was no effect of farming system on second generation oviposition ($F_{3,7.99} = 0.02$; $p = 0.9955$), but significant effect of sampling week ($F_{3,473} = 156.54$; $p < 0.0001$) with different levels of oviposition among all 4 weeks (Tukey–Kramer adjustment: $p < 0.0001$; Fig. 1b).

Oviposition of first generation *D. radicum* in 2009 was affected by farming system ($F_{3,5.98} = 14.05$; $p = 0.0041$) and sampling week ($F_{2,336} = 11.84$; $p < 0.0001$) but not their interaction ($F_{6,336} = 0.86$; $p = 0.5250$). Significantly fewer eggs were laid in O3 (1.3–2.2 eggs/plant/week) than in the other three systems (4.1–7.8 eggs/plant/week; Tukey–Kramer adjustment: $p < 0.02$) and overall oviposition was higher in the third week than in the two first weeks of sampling (Tukey–Kramer adjustment: $p < 0.01$). Oviposition by second generation *D. radicum* was significantly affected by farming system ($F_{3,50.7} = 6.39$; $p = 0.0009$; Fig. 1c) and sampling week ($F_{2,292} = 40.58$; $p < 0.0001$) and not their interaction ($F_{6,292} = 0.74$; $p = 0.6141$). As in the first generation, significantly fewer eggs were laid in O3 compared to the other three systems (Tukey–Kramer adjustment: $p < 0.01$) and overall oviposition decreased from the first to second to third week of sampling (Tukey–Kramer adjustment: $p < 0.005$). In summary, no consistent effect of farming system on oviposition was seen over the 3 years of sampling, with most eggs being laid in O3 in 2007, no differences observed in 2008, while fewest eggs were laid in O3 in 2009. Over the 3 years, the overall levels of oviposition decreased at the field site (Fig. 1).

After the first growing season of the field experiment in 2006, the numbers of overwintering *D. radicum* puparia in the soil around cabbage plants were significantly affected by the farming system ($F_{3,5.89} = 6.32$; $p = 0.0284$; Fig. 2). Significantly more overwintering puparia were found in the conventional system C compared to the organic system O1 (Tukey–Kramer adjustment: $p = 0.0239$) and numbers of puparia in C compared to O2 and O3 were close to be significantly higher (Tukey–Kramer adjustment: $p = 0.0779$ and $p = 0.1055$, respectively). In 2007, there was no significant effect of farming system on the number of overwintering puparia ($F_{3,6} = 2.37$; $p = 0.1697$; Fig. 2). However, significant effects of farming system were found in the following two seasons, with most puparia per plant in C compared to the three organic systems in 2008 ($F_{3,6} = 11.54$; $p = 0.0067$; Fig. 2, Tukey–Kramer adjustment; $p < 0.05$), and in 2009 ($F_{3,138} = 4.63$; $p = 0.0040$; Fig. 2) with more puparia collected from C than from O2 and O3 (Tukey–Kramer adjustment: $p < 0.03$).

The estimated proportions of second generation *D. radicum* eggs reaching the pupal stage in each plot ranged between 0.010 and 0.103 and these proportions were significantly affected by a farming system and year interaction ($F_{6,22} = 3.58$; $p = 0.0126$). In 2007 and 2008, survival rates were significantly higher in C compared

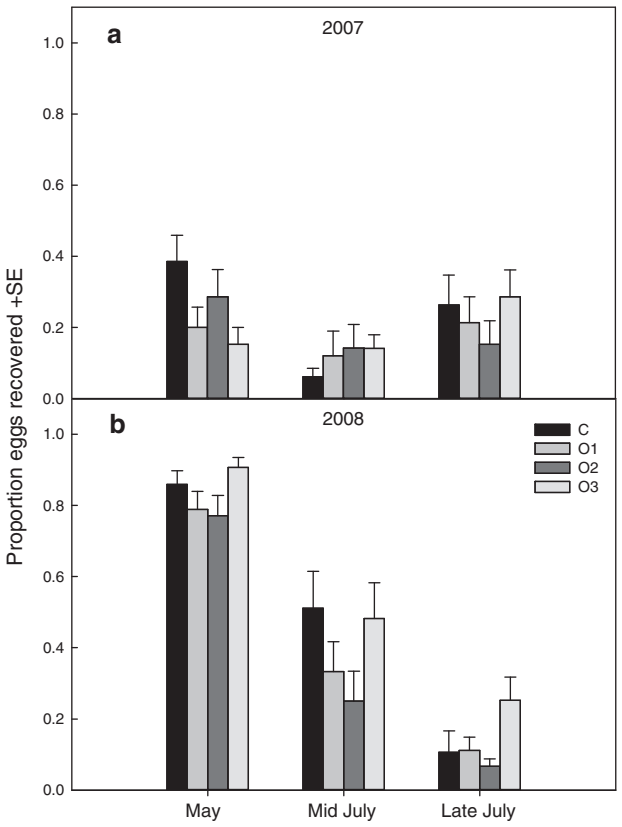

Fig. 3. Mean proportions (+S.E.) of recovered sentinel *M. domestica* eggs at three occasions in 2007 (a) and 2008 (b) in four farming systems (abbreviations cf. Table 1).

to all three organic systems, while the estimated survival rate in C in 2009 was significantly higher than in O1 and O2 (Tukey–Kramer adjustment: $p < 0.05$).

3.1. Parasitoids and predators

Mean proportions (±S.E.) of the overwintering *D. radicum* puparia containing parasitoids ranged from 0.265 (±0.087) to 0.595 (±0.027) per farming system, but were always above 0.5 in O2. However, in neither of the 4 years 2006–2009 significant differences in proportions of puparia with parasitoids were found among the farming systems. Parasitoids belonged either to *T. rapae* or *A. bilineata* in all 4 years, and the relative distributions of the two parasitoid species between parasitized puparia varied significantly among years with *T. rapae* constituting 91.0% of all parasitoids in 2006, 46.0% in 2007, 78.8% in 2008 and 40.0% in 2009 ($\chi^2 = 401.1185$; df = 3; $p < 0.0001$). In 3 of the 4 years, a trend was indicated that highest proportions of *T. rapae* among the parasitoids were found in O3, but this was only significant in 2006 and close to significance ($p = 0.0512$) in 2009 (Table 2).

Egg predation rates were estimated as proportions of fly eggs recovered after 24 h exposure in the plots, thus the more eggs recovered the less predation estimated. The recovered mean proportions of control eggs enclosed by plastic cylinders ranged between 0.86 and 0.93 in 2007 and 0.92 and 1.0 in 2008, which on all occasions were significantly higher than freely exposed eggs in the four farming systems (May 2007: $p < 0.02$; July 2007: $p < 0.0001$; May 2008: $p < 0.001$; and July 2008: $p < 0.0001$). The control treatments were therefore excluded from the data, which were then analyzed for system effects in four mixed models for each of the four oviposition periods. In May 2007, there was a significant effect of farming system ($F_{3,52} = 7.75$; $p = 0.0002$; Fig. 3a) with more eggs being recovered in C than in O1 and O3 (Tukey–Kramer adjustment: $p = 0.0057$ and $p = 0.0003$, respectively), and more in O2 than in O3 (Tukey–Kramer adjustment: $p = 0.0427$). A significant interaction between farming system and experimental week existed for July 2007 ($F_{3,46} = 3.19$; $p = 0.0324$), but the only significant differences in egg recovery were seen between the two experimental weeks in C (Tukey–Kramer adjustment: $p = 0.0059$) and in O3 (Tukey–Kramer adjustment: $p = 0.0295$) with recovery being highest in the latter week (Fig. 3a). For the experimental week in May 2008 egg recovery was generally high (Fig. 3b) and a significant farming system effect was found ($F_{3,62} = 4.61$; $p = 0.0056$) with higher egg recovery in O3 compared to O1 and O2 (Tukey–Kramer adjustment: $p = 0.0225$ and $p = 0.0084$, respectively). In July 2008, there was a significant interaction between farming system and experimental week ($F_{3,65} = 5.11$; $p = 0.0031$). However, all significant differences were between the two experimental weeks and no significant differences were found among farming systems within individual weeks. Overall, significant egg predation was found in all four farming systems, but no consistent differences among the systems were seen although a trend was indicated that predation in 2008 was lowest in O3 (Fig. 3b).

Numbers of selected species of small carabids combined with individuals < 8 mm of Aleocharinae ("small beetles") caught per trap were in 2007 affected by a significant interaction between farming system and sampling week ($F_{6,196} = 7.64$; $p < 0.0001$) indicating differential patterns of catches among farming systems over time. In May, a mean (±S.E.) of 20.1 (±2.26) small beetles were caught per trap in O2 which was significantly higher than in the other three farming systems (Tukey–Kramer adjustment: $p < 0.001$). No differences were found among farming systems in the two sampling weeks in July 2007. For collections in 2008, there was no significant interaction between farming system and sampling week ($F_{6,201} = 1.98$; $p = 0.07$) but individual effects of farming system ($F_{3,201} = 12.27$; $p < 0.0001$) and sampling week ($F_{2,201} = 32.03$; $p < 0.0001$). During the three sampling weeks, mean beetle numbers (±S.E.) per trap ranged between 17.8 (±1.42) and 26.5 (±2.30) in O2 which were significantly higher than in the three other systems (Tukey–Kramer adjustment: $p < 0.05$). Total catches in 2008 were significantly different among the 3 weeks, lowest in May and highest during the first collection in July (Tukey–Kramer adjustment: $p < 0.0004$).

Total egg predation and number of potential egg predators in each experimental plot were not significantly correlated in May 2007 (Spearman correlation coefficient = 0.28142; $p = 0.3756$; $n = 12$), July 2007 (Spearman correlation coefficient = −0.16204; $p = 0.4494$; $n = 24$), May 2008 (Spearman correlation coefficient = −0.44211; $p = 0.1501$; $n = 12$) or in July 2008 (Spearman correlation coefficient = 0.31236; $p = 0.1373$; $n = 24$).

For three of the four *Bembidion* species caught, most individuals were found in May in both years, and pitfall catches for May in 2007 and 2008 of each of the three species were analyzed separately. Significant effects of farming system (*B. lampros*: $F_{3,66} = 19.62$, $p < 0.0001$; *B. quadrimaculatum*: $F_{3,66} = 20.10$, $p < 0.0001$; *B. tetracolum*: $F_{3,66} = 24.19$, $p < 0.0001$) and year (*B. lampros*: $F_{1,68} = 6.55$, $p = 0.0127$; *B. quadrimaculatum*: $F_{1,68} = 5.09$, $p = 0.0273$; *B. tetracolum*: $F_{1,68} = 5.88$, $p = 0.0180$) were found for each species while none of the interactions were significant. Thus farming system effects were consistent between years, but overall catches were different between the 2 years. For all the three species, most individuals were caught in the organic system O2 (Table 3). Individuals of the generalist predator *Pterostichus melanarius* (Illiger) were predominantly caught in July in both 2007 and 2008 with no significant interaction between farming system and year ($F_{3,210} = 2.04$, $p = 0.1088$). During July, means (±S.E.) of individuals caught per pitfall trap equalled 2.9 (±0.34) in C, 3.6 (±0.46) in O1, 3.8 (±0.39) in O2, and 3.0 (±0.34) in O3. No differences were seen in

Table 2
Mean proportions (S.E.) of parasitized puparia harbouring *Trybliographa rapae* in each of four farming systems per year.

Year	Farming system[a]				Summary statistics	
	C	O1	O2	O3	*F*-Value	*p*
2006	0.838 (0.023)	0.882 (0.044)	0.951 (0.020)	0.971 (0.017)	$F_{3,98} = 4.67$	0.0043
2007	0.604 (0.049)	0.457 (0.091)	0.420 (0.082)	0.340 (0.060)	$F_{3,82} = 1.34$	0.2683
2008	0.800 (0.069)	0.563 (0.175)	0.806 (0.092)	0.871 (0.057)	$F_{3,49} = 0.68$	0.5678
2009	0.312 (0.067)	0.269 (0.070)	0.427 (0.085)	0.675 (0.094)	$F_{3,86} = 2.69$	0.0512

[a] Abbreviations cf. Table 1.

Table 3
Mean number (S.E.) of *Bembidion* spp. caught per pitfall trap in May combined for 2007 and 2008 for each farming system ($n = 36$). For each species, means followed by different letters are significantly different (Tukey–Kramer adjustment, $p < 0.05$).

	Farming system[a]			
	C	O1	O2	O3
Bembidion lampros	3.3 (0.46) a	3.3 (0.39) a	6.1 (0.70) b	1.4 (0.22) c
Bembidion quadrimaculatum	0.9 (0.19) a	2.3 (0.39) b	4.1 (0.51) c	1.4 (0.17) ab
Bembidion tetracolum	0.6 (0.14) a	1.3 (0.36) a	2.9 (0.44) b	0.2 (0.09) c

[a] Abbreviations cf. Table 1.

activity-density of *P. melanarius* among the four farming systems ($F_{3,65.9} = 1.52$, $p = 0.2178$) while the effect of year was significant ($F_{1,210} = 148.70$, $p < 0.0001$) with fewest beetles caught in 2008.

4. Discussion

The field experiment demonstrated that the three organically farmed cabbage production systems provided enhanced regulation of *D. radicum* measured by puparia/egg ratios over a conventionally farmed system. However, no clear differences were observed among the four experimental cropping systems on *D. radicum* oviposition. The intercropped strips of green manure in O3 were hypothesized to reduce the oviposition by *D. radicum* females as documented for intercropped clover within *Brassica* crops (Tukahirwa and Coaker, 1982; Finch and Collier, 2000a; Bjorkman et al., 2007, 2010), but oviposition was only found to be lowest in O3 in 2009 while it was highest in 2007. Tukahirwa and Coaker (1982) showed that the distance from host plant to intercropped non-host plant should be <50 cm to significantly reduce oviposition rates of *D. radicum*. The maximum distance in the present study was 40 cm. However, cabbage plants were only neighbouring green manure strips to one side, and the intercropped strips in O3 may thus have been inappropriately positioned to yield a continuous confusion effect as described by Finch and Collier (2000a). These strips are therefore unlikely to reduce oviposition of *D. radicum* in a pest management strategy in cabbage cropping systems.

Since oviposition in C was not consistently higher than in the three organic systems the results indicate that *D. radicum* survival from egg to pupation was increased in C compared to the organic systems. In the present study, small beetle abundance, including *Bembidion* spp., was generally highest in O2, suggesting enhanced predation in this organic system. The method of using sentinel *M. domestica* eggs proved useful for evaluating predation rates, but it was not possible to attribute the indicated superior survival of *D. radicum* from egg to pupation in C to reduced egg predation in the conventional system compared to the organic systems. Lack of correlations between egg removal and abundance of egg predators in experimental plots was also reported by Prasad and Snyder (2006) and Bjorkman et al. (2010) despite increased pupal production when potential egg predators were excluded (Bjorkman et al., 2010). The egg predation effect of small beetles could be compromised either by the presence of alternative prey or intraguild predation by large carabids such as *P. melanarius* (Prasad and Snyder, 2006). However, activity-densities of *P. melanarius* were equal among farming systems in the present study. Habitat heterogeneity provided by the intercropped strip of green manure in O3 did not benefit small beetles known to be egg predators, particularly *Bembidion* spp. which are more abundant in open ground habitats than in areas with increased ground cover (Eyre et al., 2009; Bjorkman et al., 2010). Although organic systems O1 and O2 had comparable ground cover small beetles were most abundant in O2. The combination of low slurry input and green manures in organic cropping systems may have benefitted small predatory beetles, though no significant differences in organic matter contents of the soil of O1 and O2 were found (K. Thorup-Kristensen, unpubl.).

Parasitism by parasitoids in second generation puparia were unaffected by the experimental farming practices. Data indicated a relative dominance of *T. rapae* in some years, and then mostly in O3, suggesting potential benefits of floral nectar resources in the strips of green manure.

Slurry was applied to all three organic systems showing reduced *D. radicum* puparia/egg ratios compared to the conventional system C, which was fertilized by synthetic fertilizers and received the highest total amounts of nutrients. Although O1 received a higher external input of nitrogen than O2 and O3, *D. radicum* survival estimates were comparable among the three organic systems indicating that the amendment of organic fertilizer may have contributed to the observed effect. The organic system O2 exhibited reduced nitrogen leaching compared to C and O1 (Thorup-Kristensen et al., 2012) and may provide most promise as a sustainable approach for organic cabbage cropping systems as it additionally benefitted small predatory beetles.

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