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The role of spiders as predators of two lepidopteran *Brassica* pests

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Abstract Spiders are thought to play a significant role in limiting pest outbreaks in agroecosystems such as vineyards, orchards and cotton. The diversity and impact of spiders in vegetable crops are less well understood, although there is evidence that predators may be important for suppression of lepidopteran pests in *Brassica* crops, particularly early in the season before parasitoids become established. Sampling was conducted in early season plantings of *Brassicas* in the Lockyer Valley (South East Queensland, Australia) in order to determine the most commonly occurring spider families. The most numerous were Theridiidae, which were more strongly associated with cauliflower and poorly associated with cabbage. The Lycosidae and Clubionidae/Miturgidae (formerly in the 'catch-all' family Clubionidae) also occurred commonly. Lycosidae (and to a lesser extent Salticidae) had above average abundance in Chinese cabbage and below average abundance in broccoli compared with average abundance for these spider families; Clubionidae/Miturgidae had above average abundance in cauliflower. Laboratory studies were then conducted to explore the predatory capacity of these three most commonly occurring spider families. All three were capable of feeding on larvae of the diamondback moth, *Plutella xylostella* (Linnaeus), and cabbage cluster caterpillar, *Crocidolomia pavonana* (Fabricius), under laboratory conditions. Theridiidae, which are thought to prey on small pests such as leafhoppers and aphids, were able to successfully attack larvae up to five times their body size. Predation rates varied from an average of 1.7 (SE = 0.47) (1.6 control corrected) larvae consumed over a 24 h period in the case of the Theridiidae, to 3.3 (SE = 0.60) larvae for the Clubionidae/Miturgidae.

Key words *Brassica*, Clubionidae, Lepidoptera, Lycosidae, Miturgidae, Theridiidae.

INTRODUCTION

There is a growing body of evidence to suggest that spiders play an important role in limiting pest outbreaks in a wide variety of agroecosystems, such as vineyards (Costello & Daane 1999; Hanna *et al.* 2003), orchards (Mansour *et al.* 1980; Mansour & Whitcomb 1986; Miliczky & Calkins 2002; Monzó *et al.* 2009) and cotton (Mansour 1987; Pfannenstiel 2008; Whitehouse *et al.* 2011). The types of spiders most prevalent in these and other crops have also been investigated. Uetz *et al.* (1999) found that certain crops (peanut, alfalfa, soybean, rice) were dominated by ground runners (e.g. Lycosidae) and web-wanderers (e.g. Linyphiidae), whereas others (corn, cotton, sugar, sorghum) were dominated by orb weavers (e.g. Tetragnathidae) and stalkers (e.g. Salticidae and Oxyopidae). Whitehouse *et al.* (2009) demonstrated that spider type and diversity within cotton were influenced by factors such as location and time of year. Similarly, Nyffeler and Sunderland (2003) found differences in spider communities in US and European agroecosystems, attributing these differences to factors such as climate, dominant crop types and farm size. However, although a number of studies have examined the range and impact of spiders in broadacre and permanent cropping systems, there have been relatively few studies in short-term vegetable crops. Examples are Riechert and Bishop (1990) and Hooks *et al.* (2006, 2007) who found that pest levels and plant damage were reduced in vegetable plots with enhanced spider densities, mainly comprising Theridiidae, Clubionidae, Oxyopidae and Lycosidae. Snyder and Wise (1999) examined the effects of manipulating immigration rates of lycosid spiders and carabid beetles on pest densities and productivity in vegetable crops. Increased predator immigration had no effect in spring plantings of cabbage, bean, eggplant and cucumber, whereas pest density was marginally lower, and productivity was increased in summer plantings of squash. However, these authors did not separate the effects of the two predators, so the contribution of the spiders to the reduction in plant damage is unknown.

A significant proportion of Queensland's *Brassica* production occurs in the Lockyer Valley, a vegetable growing region in the south east of the state, approximately 80 km west of Brisbane. In this area, the *Brassica* cropping season extends from February (early season) through to early November (late season) (Heisswolf *et al.* 2004). Two of the most damaging lepidopteran pests attacking *Brassica* crops in South East Queensland are cabbage cluster caterpillar, *Crocidolomia pavonana* (Fabricius) (Lepidoptera: Crambidae), which causes damage early in the season, and the diamondback moth, *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae), a key pest later in the season (Zalucki *et al.* 2009). *P. xylostella* is a serious pest worldwide, with the annual worldwide cost of control in *Brassica* vegetable crops estimated at US$1.4bn (Zalucki *et al.* 2012). Its ability to develop resistance to all major classes of insecticides (Furlong *et al.* 2013) makes non-chemical management methods, such as exploitation of naturally occurring predators and parasitoids,

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an important component of any control strategy for this pest. Although insecticides are generally effective for control of *C. pavonana*, their use early in the season disrupts the integrated pest management strategy established for *P. xylostella* later in the year. There is evidence that predators may be responsible for a substantial proportion of mortality of lepidopteran pests such as *P. xylostella* (Furlong *et al.* 2004a,2004b) and *Pieris rapae* (L.), cabbage white butterfly, (Schmaedick & Shelton 1999). This is particularly significant early in the season, before the parasitoids of *P. xylostella* become established (Furlong & Zalucki 2007). Predators are also likely to be important for *C. pavonana*, as only low levels of parasitism have been observed for this pest (Sastrosiswojo & Setiawati 1992; Saucke *et al.* 2000).

Spiders were sampled in early season, unsprayed plantings of *Brassicas*, in order to determine the most commonly occurring groups, and whether these varied between different *Brassica* cultivars. Additional sampling was conducted in *Brassica* crops at farms in the Lockyer Valley region in order to obtain data from commercial plantings. A series of laboratory studies was then performed with each of the most abundant spider families with the aim of exploring the predatory capacity of each on two lepidopteran *Brassica* pests. The three spider families selected for the laboratory studies represented three different spider guilds: space web builders (Theridiidae), ground running hunters (Lycosidae) and foliage running hunters (Clubionidae/Miturgidae) (Uetz *et al.* 1999).

MATERIALS AND METHODS

Field trials

Sampling was conducted in unsprayed and commercial *Brassica* plantings in the Lockyer Valley. Crops were planted in February (2009 and 2010, respectively), representative of an early season planting in the region.

Unsprayed plantings

In 2009, unsprayed plantings of broccoli, *Brassica oleracea* L. var. *italica*, (commercial variety 'Atomic'), cabbage, *B. oleracea* L. var. *capitata*, (commercial variety 'Warrior'), cauliflower, *B. oleracea* L. var. *botrytis* (commercial variety 'Freemont') and Chinese cabbage, *B. rapa* var. *pekinensis* (commercial variety 'Matilda') were established at Gatton Research Station (Lockyer Valley, Queensland) (27°32' S, 152°19' E, elevation 98 m) using a randomised complete block design with four replicates. Each replicate block (20 × 50 m) was divided into four plots, each planted with a different *Brassica* cultivar. *Brassicas* were planted in double rows, 12 rows per plot, with industry standard between-plant spacings of 0.33 m for broccoli and Chinese cabbage, and 0.66 m for cabbage and cauliflower. There were approximately 875 broccoli/Chinese cabbage, or 445 cabbage/cauliflower per plot. Plants were sampled over a 10 week period, from transplanting (26 February 2009) to harvest (5 May 2009).

Plants were inspected on 10 occasions at approximately weekly intervals commencing 1 week post transplanting. At the 8 and 10 week assessments, five plants were selected at random from each replicate plot. At all remaining assessments, 10 plants were selected. Different plants were sampled at each assessment. Each plant and the ground immediately surrounding it were examined carefully, working from the ground upwards, and all spiders recorded. Spiders were identified to family only. For the majority of assessments, examination of intact plants and identification of spiders were performed *in situ*. At the 4, 8 and 10 week assessments, the selected plants were harvested, placed in sealed bags and examined in the laboratory, enabling a more thorough inspection to be performed. Comparison of the harvested and *in situ* assessments found that although inspecting plants *in situ* resulted in slightly fewer numbers of spiders overall, it had no apparent effect on the types of spiders found or the proportions of each. Spiders collected over the 10 week period were combined for the analysis.

As an additional method of sampling ground-dwelling spiders, pitfall traps were placed in the crops for the duration of the trial. Based on the methodology of Furlong *et al.* (2004b), each trap consisted of a 275 mL plastic cup placed within a second, larger cup (320 mL), buried with the rim level with the soil surface. Traps were half-filled with a weak detergent solution and covered with a plastic disc (18 cm diameter), supported approximately 3 cm above the soil surface. Three pitfall traps were placed in each replicate of each *Brassica* type and were examined and replaced weekly. The traps remained open for the duration of the trial. Many small trapped spiders were difficult to identify because the traps often became muddy, and the trap contents did not survive intact. For the purposes of reporting, spiders found in pitfall traps were therefore identified only as Lycosidae or 'other'.

The total number of spiders recorded per plant over the 10 sampling occasions was calculated for each spider group in each *Brassica* cultivar and subjected to analysis of variance (ANOVA). A $\log_{10}$ transformation was applied in order to meet the assumptions of the ANOVA. Additionally, total numbers of spiders per plant were analysed using partial redundancy analysis (RDA) (Legendre & Legendre 1998) to examine the relationship between spider family composition and *Brassica* cultivar. The replicate blocks were fitted as conditional variables, and an ordination biplot was prepared to represent the relationship between the *Brassica* cultivars and the spider groups. A large proportion of spiders were juveniles and could not be identified with confidence. Although these spiders were recorded, they were not included in the statistical analyses. The mean total number of Lycosidae and other spiders caught per pitfall trap over the trial period was calculated. Pitfall trap data were analysed separately from the data obtained from the visual inspections of plants. All statistical analyses were performed in GenStat for Windows 16th Edition (VSN International 2013).

Commercial plantings

In 2010, sampling was carried out at three *Brassica* farms in the Lockyer Valley region, situated within 20 km of Gatton

Research Station. Two farms were organic, and the third used selective insecticides that were expected to have minimal impact on spiders. Two sites were sampled at each farm, resulting in six sampling sites, treated as replicates for the purpose of statistical analysis. Sites were planted with broccoli, cabbage or cauliflower. Visual inspections of plants and the ground immediately surrounding each plant were carried out approximately weekly, from shortly after transplanting (February 2010) for between 7 and 9 weeks, dependant on sampling site. At each inspection, 30 plants per site were inspected *in situ*. In addition, five pitfall traps were placed at each site and examined twice weekly for the duration of the trial.

The total number of spiders per plant was calculated for each spider group, corrected for differences in length of sampling period, and subjected to ANOVA. A $\log_{10}$ transformation was applied in order to meet the assumptions of the ANOVA. Unidentified spiders were not included in the analysis. The mean total number of Lycosidae and other spiders caught per pitfall trap over the trial period was calculated and corrected for differences in length of sampling period.

School of Life Sciences, University of Queensland (*P. xylostella* and *C. pavonana*). Larvae of a similar size (approximately 5 mm in length) were selected for the experiment, and hence exact instar differed depending on species. Five moth larvae (*P. xylostella* or *C. pavonana*) were placed on the plant and allowed to settle for a minimum of 30 min. A single spider was placed in each cage, Theridiidae and Clubionidae/Miturgidae on the foliage and Lycosidae on the soil surface at the base of the plant. This method allowed the spiders to interact with their potential prey in a semi-natural arena, for instance, the Theridiidae were observed to build webs. Ten replicates were performed for each spider type provided with each prey species. An additional ten control replicates were performed for each prey species with no spider present in order to account for natural mortality and escaping larvae. Observations were made at 24 h, and the numbers of live, dead and missing larvae per plant were recorded. Any missing larvae were assumed to have been consumed.

An adaptation of Abbott's formula (Gavish-Regev *et al.* 2009) was applied to the means of the raw data to correct for control mortality:

$$Corrected\ \ prey\ \ survival = \left(\frac{Number\ \ surviving\ \ prey\ \ in\ \ spider\ \ treatment}{Number\ \ surviving\ \ prey\ \ in\ \ control}\right) * \ original\ \ number\ \ of\ \ prey$$

Laboratory trials

Spiders

Theridiidae, Lycosidae and Clubionidae/Miturgidae, the most abundant of the identified spiders in the field sampling trials, were selected for assessment in the laboratory. It should be noted that Clubionidae and Miturgidae were both formerly in the 'catch-all' family Clubionidae. As these two families were not distinguished during field sampling experiments, they were also treated as one group for the purpose of the laboratory experiments. Spiders were not identified beyond family, nor were they sexed; however, spiders of similar appearance and size were selected for use in experiments (with the exception of theridiid spiders, where a range of sizes were used). Spiders were collected from the unsprayed *Brassica* plantings at Gatton Research Station where the 2009 sampling was conducted, and hence were representative of the spiders present in those crops.

Spiders were collected in the weeks prior to use in each experiment (various occasions between December 2009 and September 2010). They were held at about 10 °C and provided with a water source (damp dental wick). Where duration of storage was longer than 14 days, they were also provided with food (*Drosophila melanogaster* Meigen); however, in all cases, spiders were starved for a minimum of 4 days prior to use in experiments.

1 ***Spider predation rates on two prey species***

Potted broccoli seedlings (about 15 cm high, five leaf stage) were enclosed within clear, cylindrical cages (10.5 cm diameter, 25 cm high) with mesh-covered ventilation holes (5 cm diameter) in the side and top. Moth larvae were obtained from cultures maintained at Gatton Research station (*P. xylostella*) and the

Corrected prey survival was used to calculate prey consumption by the spiders. In addition, the numbers of dead plus missing larvae were subjected to ANOVA, with spider type (Lycosidae, Theridiidae, Clubionidae/Miturgidae and no spider control) and prey type (*P. xylostella* and *C. pavonana*) as factors. Pairwise comparisons using Fishers' protected 95% least significant difference were conducted to distinguish between the group means. An arcsine transformation was applied in order to meet the assumptions of the statistical test.

2 ***Predation rates of Clubionidae/Miturgidae***

An experiment was performed to further examine the number of *P. xylostella* larvae consumed per day by clubionid/miturgid spiders. A single spider was placed on a caged broccoli seedling and provided with five fourth instar *P. xylostella* larvae (approximately 10 mm in length). Observations were made after 24, 48 and 72 h. At each assessment, the numbers of live, dead and missing larvae per plant were recorded. Any missing or pupating larvae were replaced, so that each spider had access to five prey items every day. Ten replicates were performed with a spider present, and five replicates with no spider present (control). Data were corrected for control mortality as described previously.

3 ***Predation rates of Theridiidae***

An experiment was performed to further examine the number of *P. xylostella* larvae consumed over a 24 h period by theridiid spiders. A single spider was placed on a caged broccoli seedling and provided with five fourth instar *P. xylostella* larvae (approximately 10 mm in length). Spiders ranged in size from 1 to 3.5 mm (abdomen width). Observations were made at 24 h, and the numbers of live, dead and missing larvae per plant were recorded. Twenty replicates were performed with a spider present and 10 replicates with no spider present (control). The average number of larvae consumed over the 24 h period was calculated. Correction for control mortality was not required as no larvae were found to be missing or dead in the control replicates.

4 ***Selection of prey size by Theridiidae***

A single theriidid spider was placed in a Petri dish (9 cm diameter) and provided with one early instar and one late instar *P. xylostella* larva (approximately 2 and 5 mm in length, respectively), placed on a broccoli leaf disc (3 cm diameter). A total of 155 spiders were assessed, ranging in size from 1 to 3.5 mm (abdomen width). Observations were made periodically for a maximum of 48 h and the first prey item attacked was recorded. Resulting data were subjected to a binomial test to compare the proportion of early and late instars selected. Where a prey selection was not made within the experimental period, or where both prey items were consumed and the first selection not observed, the replicate was recorded as void and was excluded from analysis.

RESULTS

Field trials

Spiders were commonly found in all *Brassica* cultivars, from seedling stage through to harvest. Spiders recorded in unsprayed *Brassica* plantings during visual inspection of the plants and surrounding ground are displayed in Figure 1. A large proportion (26%) of the spiders could not be identified with confidence *in situ*. The majority of these were juveniles. The most numerous of the identified spider families overall was the Theridiidae, followed by the Lycosidae and the Clubionidae/Miturgidae, a statistically significant difference ($F = 146.88$; df = 5, 69; $P < 0.001$, Table 1). There was also an effect of *Brassica* cultivar ($F = 10.47$; df = 3, 69; $P < 0.001$), with most spiders found in Chinese cabbage and cauliflower and fewest in broccoli and cabbage (Table 2). There was a significant interaction between spider type and *Brassica* cultivar ($F = 4.00$; df = 15, 69; $P < 0.001$) (Fig. 1). For instance, the Salticidae were more numerous in Chinese cabbage and the Clubionidae/Miturgidae more numerous in cauliflower.

Table 1 Group means for spider type (total spiders per plant over the experimental period), sampled through visual inspection of plants and surrounding ground in unsprayed *Brassica* plantings

	Group means of spiders per plant †	
Spider	Log_{10} transformed ‡	Back-transformed
Theridiidae	0.68 a	3.80
Lycosidae	0.53 b	2.36
Clubionidae/Miturgidae	0.29 c	0.95
Salticidae	0.12 d	0.33
Oxyopidae	0.08 d	0.21
Araneidae	0.02 e	0.05

†Standard errors of spider group means = 0.02

‡Means followed by the same letter are not significantly different ($P > 0.05$)

The partial redundancy analysis found that the *Brassica* cultivars explained 43% of the variation in the spider composition. Within this, the first two axes explained 96%, and an ordination biplot showing the first two axes is given in Figure 2. The biplot of spider groups and *Brassica* cultivars indicated that Theridiidae had above average abundance on cauliflower and below average abundance on cabbage compared with the average abundance for Theridiidae. Clubionidae/Miturgidae also had above average abundance in cauliflower compared with the average for this spider group. Lycosidae and Salticidae were correlated, and both had above average abundance in Chinese cabbage and below average abundance in broccoli. The

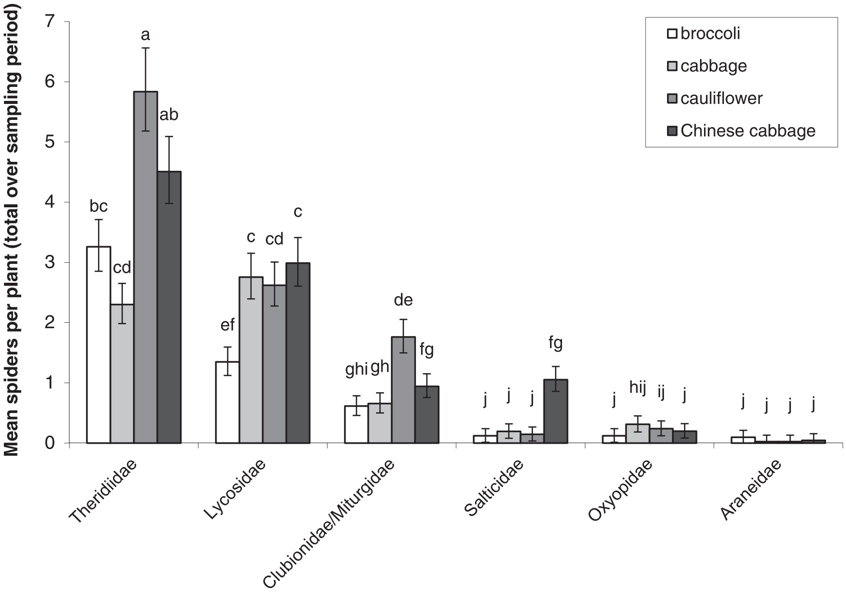

Fig. 1. Family composition of spiders sampled through visual inspection of plants and surrounding ground in unsprayed *Brassica* plantings. Data are back-transformed total spiders per plant over the experimental period (means ± standard errors). Means with common letters are not significantly different ($P > 0.05$).

Table 2 Group means for *Brassica* cultivar (total spiders per plant over the experimental period), sampled through visual inspection of plants and surrounding ground in unsprayed *Brassica* plantings

	Group means of spiders per plant [†]	
Cultivar	Log_{10} transformed [‡]	Back-transformed
Broccoli	0.22 a	0.68
Cabbage	0.25 a	0.79
Cauliflower	0.33 b	1.15
Chinese cabbage	0.34 b	1.19

[†] Standard errors of crop group means = 0.02

[‡] Means followed by the same letter are not significantly different ($P > 0.05$)

Araneidae and Oxyopidae were not highly correlated with other spider groups nor with a *Brassica* cultivar.

Sampling in commercial *Brassica* plantings also found that the Theridiidae were the most numerous of the identified spiders, followed by the Lycosidae and the Clubionidae/Miturgidae ($F = 22.87$; df = 7, 35; $P < 0.001$) (Fig. 3). Two families (Thomisidae and Tetragnathidae) were found in the commercial plantings but not the non-commercial unsprayed plantings. Unidentified spiders (the majority of which were juveniles) were those that could not be identified *in situ* and accounted for 32% of the sampled spiders.

Pitfall trapping confirmed that Lycosidae were the most numerous of the ground-dwelling spiders. Traps placed in unsprayed plantings caught more Lycosidae than other types of spider (Fig. 4). Traps in commercial plantings caught equal numbers of Lycosidae and other spider types; total trap catch over the trial period was 4.9 (SE = 0.6) Lycosidae and 4.9 (SE = 0.6) other spider species per trap.

Specimens from each of the three most commonly observed spider groups were identified by Owen Seeman (Queensland Museum, Brisbane) as *Artoria* sp. (Lycosidae), *Cryptachaea veruculata* (Urquhart) (formerly *Achaearanea*) (Theridiidae), *Cheiracanthium gilvum* L. Koch (Miturgidae) and *Clubiona* sp. (Clubionidae). These specimens were deposited at the Queensland Museum.

Laboratory trials

1 ***Spider predation rates on two prey species***

Average prey consumption varied according to spider and prey type, with the highest average consumption of 3.3 (SE = 0.60) *P. xylostella* larvae consumed by a clubionid/miturgid spider over the 24 h trial period (Table 3). There was a significant overall effect of spider (Lycosidae, Theridiidae, Clubionidae/Miturgidae or no spider control) on prey mortality ($F = 16.52$; df = 3, 72; $P < 0.001$). All treatments containing a spider resulted in higher mortality compared with the no spider control; however, there were no differences between the three spider families. There was no effect of prey type ($F = 0.04$; df = 1, 72; $P > 0.05$) and no interaction between spider type and prey type ($F = 1.52$; df = 3, 72; $P > 0.05$).

2 ***Predation rates of Clubionidae/Miturgidae***

Clubionid/miturgid spiders provided with fourth instar *P. xylostella* larvae consumed at least one larva per day on average (Table 4).

3 ***Predation rates of Theridiidae***

Theridiid spiders provided with fourth instar *P. xylostella* larvae consumed an average of 2.1 (SE = 0.37) larvae over a 24 h period. Spiders across the size range (1 to 3.5 mm abdomen width) were observed to attack and consume the larvae.

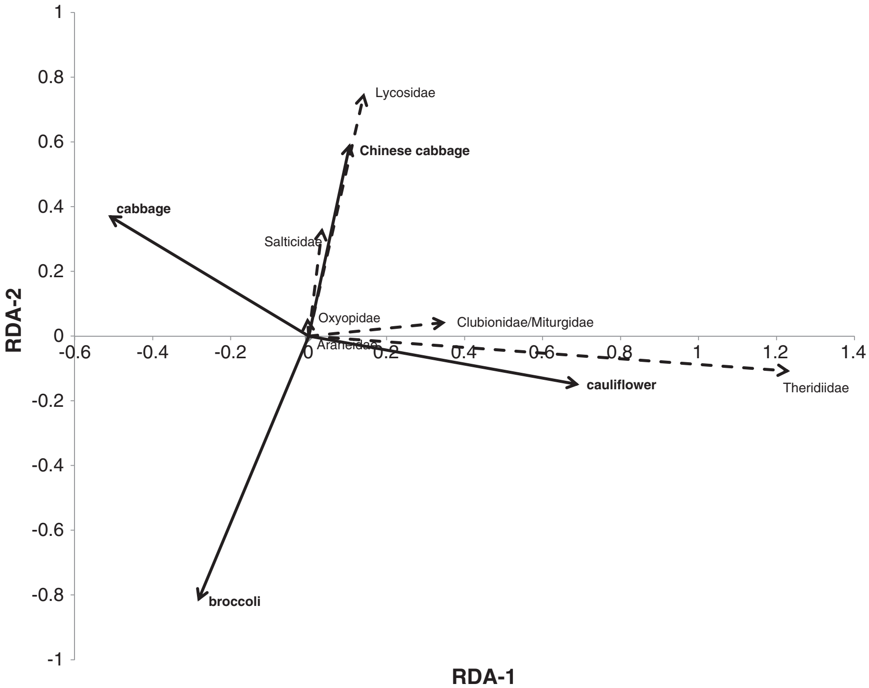

Fig. 2. Biplot for *Brassica* cultivar (solid lines) and spider groups (dotted lines) calculated using partial redundancy analysis (RDA).

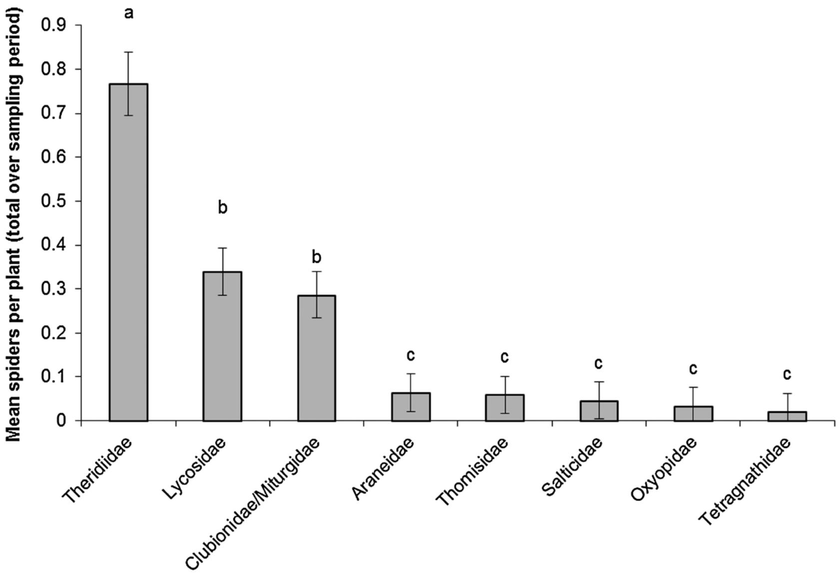

Fig. 3. Family composition of spiders sampled through visual inspection of plants and surrounding ground in commercial plantings of *Brassicas*. Data are back-transformed total spiders per plant over the experimental period (means ± standard errors). Means with common letters are not significantly different ($P > 0.05$).

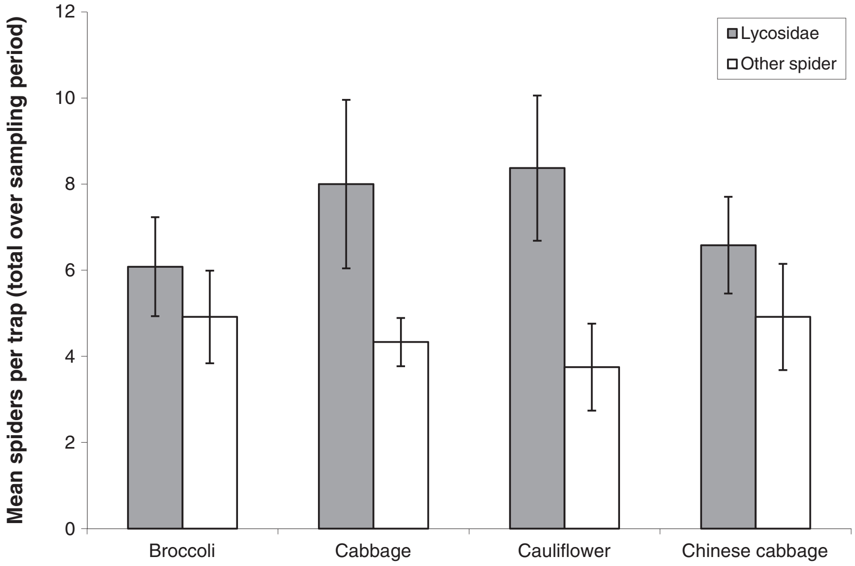

Fig. 4. Pitfall trap catch in unsprayed *Brassica* plantings: total spiders per trap over the experimental period (means ± standard errors).

4 *Selection of prey size by Theridiidae*

Of the 155 spiders assessed, 45 (29%) attacked the smaller larva and 39 (25%) attacked the larger larva, with 71 (46%) void (no selection made within the experimental period or both prey items consumed and first selection not observed). There was no significant difference between the proportion of large and small prey attacked ($P = 0.585$). Theridiid spiders as small as 1 mm (abdomen width) were able to successfully attack *P. xylostella* larvae up to 5 mm in length, i.e. approximately five times their own body size.

DISCUSSION

Visual inspection of plants and surrounding soil revealed that the most numerous spiders in early season *Brassica* plantings were Theridiidae, accounting for up to 49% of identified spiders in the unsprayed plantings, depending on *Brassica* cultivar, and 48% in commercial plantings. The grouped Clubionidae/Miturgidae and the Lycosidae were also found commonly in the sampled *Brassica* crops. In a similar study, Furlong *et al.* (2004b) found Clubionidae, Oxyopidae and

Table 3 Number of moth larvae consumed by spiders over a 24 h period (means ± standard errors). Each spider was confined on a broccoli seedling with five larvae in a no-choice test

Spider	Prey type †		Group means of larvae consumed per spider ‡
	Plutella xylostella	*Crocidolomia pavonana*	
Lycosidae	1.9 ± 0.43	2.9 ± 0.50	0.75 a (2.3)
Theridiidae	2.6 ± 0.60	1.7 ± 0.47 [1.6]	0.67 a (1.9)
Clubionidae/ Miturgidae	3.3 ± 0.60	2.6 ± 0.69	0.93 a (3.2)
Control (no spider)	0 ± 0	0.1 ± 0.1	0.02 b (0.0)

†Control corrected data, where different from pre-corrected data, in square brackets

‡Arcsine transformed data (back transformed means in brackets). Means followed by the same letter are not significantly different ($P > 0.05$)

Table 4 Number of larvae eaten by clubionid/miturgid spiders over each of three consecutive 24 h periods (means ± standard errors). Each spider was confined on a broccoli seedling with five moth larvae in a no-choice test

Treatment	Hours post set-up †		
	24	48	72
Spider	1.2 ± 0.36	1.9 ± 0.41	1.4 ± 0.43 [1.1]
Control (no spider)	0 ± 0	0 ± 0	0.4 ± 0.24

†Control corrected data, where different from pre-corrected data, in square brackets

Lycosidae to be the most common spiders in commercial cabbage crops in the Lockyer Valley (QLD, Australia). Although Oxyopidae were found in the current study, they formed a relatively small proportion of the spider fauna. It is possible that this discrepancy between the two studies may have been related to the time of year each was conducted: Furlong *et al.* (2004b) sampled from June to August, whereas the current trial was conducted earlier in the year (end of February to beginning of May). Whitehouse *et al.* (2009) found that spider communities in Australian cotton at central latitudes changed during the cotton growing season (December to February), with Clubionidae dominating early and late in the season. Numbers of Oxyopidae declined towards the end of the season (M Whitehouse, pers. comm. 2013).

Outside of Australia, several studies have reported that Theridiidae, Lycosidae and Oxyopidae are the most common spiders in vegetable crops. Riechert and Bishop (1990) found sheet-scattered line weavers (e.g. Theridiidae) were the most numerous spider group in mixed vegetable plantings in Tennessee (USA), followed by diurnal hunters (e.g. Lycosidae and Oxyopidae). Sampling in *Brassica* crops in Hawaii (USA), Hooks *et al.* (2003, 2006, 2007) consistently found large numbers of Theridiidae, Oxyopidae and Clubionidae. Ground dwelling predators were not sampled.

Lycosidae were the most frequently caught spider in pitfall traps in the current study, found consistently at all sampling sites throughout the trial period. This agrees with findings of previous studies sampling predator populations in *Brassica* crops (Furlong *et al.* 2004b; Hosseini *et al.* 2008, 2012; Miranda *et al.* 2011; Liu *et al.* 2013). Schmaedick and Shelton (2000) also commonly found Lycosidae in pitfall traps placed in cabbage plantings (New York State, USA), although Linyphiidae were more numerous.

Sampling in unsprayed plantings in the present trial found that Lycosidae and Salticidae had above average abundance in Chinese cabbage and below average abundance in broccoli. Theridiidae and Clubionidae/Miturgidae had above average abundance in cauliflower and below average abundance in cabbage. This may be due in part to the different spectrum of pests found in these crops. It was observed that the broccoli, cabbage and cauliflower had relatively high numbers of lepidopteran pests compared with the Chinese cabbage, whereas this latter crop supported large populations of aphids and leafhoppers. The differing structures of the four *Brassica* cultivars may also have influenced the distribution of the spiders. For instance, Uetz *et al.* (1999) found large variations in spider guild structure in different crop types and suggested that this was linked to structural complexity of the crops.

The relative number of spiders in unsprayed *Brassica* crops on the research station was higher than in commercially managed crops. It is likely that this difference was mainly due to the larger pest populations in the unsprayed crops. The unsprayed crops were also subject to less disturbance than the commercial crops.

Laboratory experiments were conducted to explore the predatory potential of the three most commonly sampled spider families (Theridiidae, Clubionidae/Miturgidae and Lycosidae) on larvae of two lepidopteran *Brassica* pests, *P. xylostella* and *C. pavonana*. All three spider families fed on larvae of *P. xylostella* and *C. pavonana* under laboratory conditions, a finding consistent with previous studies. For instance, Hosseini *et al.* (2012) found that, dependent on species, between 35% and 100% of Lycosidae sampled from *Brassica* crops tested positive for the presence of *P. xylostella* in the gut contents. According to Carroll (2012), the miturgids *Cheiracanthium inclusum* (Hentz) and *C. mildei* L. Koch are effective predators of caterpillars in vineyards. Pérez-Guerrero *et al.* (2013) confirmed the feeding potential of the miturgid *C. pelasgicum* (C.L. Koch) on lepidopteran larvae in the laboratory and Maloney *et al.* (2003) listed caterpillars amongst the prey of Miturgidae and Clubionidae.

Theridiidae, the most numerous of the foliage-dwelling spiders in the current study, are generally thought to prey on small pests such as leafhoppers and aphids (Bishop & Blood 1981). Consequently, the potential of these small spiders for suppression of larger crop pests, such as Lepidoptera, has often been ignored. However, the current trial suggests that they are able to prey upon lepidopteran larvae and, moreover, that they are able to successfully attack larvae substantially larger than themselves. It should be noted that while the majority of the feeding experiments in the current study were performed on caged plants, allowing the theridiid spiders to construct webs, the experiment examining selection of prey size by these spiders was conducted in Petri dishes. The use of this artificial arena could have impacted on the behaviour of the web-building theridiids, and it is possible that in the field, these spiders would be less likely to select larger prey. Nevertheless, these experiments showed that theridiids are capable of preying on large prey items. Likewise, the caged plant experiments, where spiders were confined under more natural conditions, clearly demonstrated the ability of the theridiid spiders to prey on lepidopteran larvae. Although not quantified, *P. xylostella* larvae were observed in the webs of Theridiidae during sampling in *Brassica* crops, suggesting that they prey on these pests in the field. Previous studies have also established that Theridiidae prey on lepidopteran pests. For instance, the use of radiotracers demonstrated that field collected theridiids (*C. veruculata*) had eaten larvae of *Helicoverpa* spp. (Room 1980). MacLellan (1973) recorded that 40% of small, 60% of medium and 40% of large *C. veruculata* collected from apple orchards (ACT, Australia) gave positive precipitin reactions for *Ephiphyas postvittana* (Walker), light brown apple moth, and that these spiders fed readily on moth larvae in laboratory tests.

No statistically significant differences were found between the predation rates of the three spider groups (Theridiidae, Clubionidae/Miturgidae, Lycosidae), with the spiders consuming an average of between two and three moth larvae per day. A number of laboratory studies have explored predation rates of spiders. However, in the majority of these experiments, spiders were confined with potential prey in a simple arena such as a Petri dish, rather than on caged plants as in the current trial. Predation rates per day on larvae of various lepidopteran species have been variously reported as 3.5 to 11 for Lycosidae (Schmaedick & Shelton 2000; Miranda *et al.* 2011), 0.8 to 9.6 for Clubionidae (Room 1980; Pearce *et al.* 2004) and 1 to 2.2 larvae for Theridiidae (Room 1980). Schmaedick and Shelton (2000) noted that *P. rapae* larvae were much less vulnerable to attack by Lycosidae when confined on a potted cabbage seedling compared with experiments conducted in small arenas, with a group of 10 Lycosidae consuming an average of only 0.9 larvae in a 24 h period.

Results of laboratory feeding experiments cannot be extrapolated to the field situation without supporting studies. In the field, spiders interact with other predators and prey in a complex food web, making it difficult to determine the impact of a single predator on a particular pest species. For instance, spiders may prey on other predators (intraguild predation), resulting in an overall decrease in predation on the target pest, or may attack alternative prey preferentially (Chang & Snyder 2004). Nyffeler and Sunderland (2003) concluded that the potential of spiders for biocontrol of pests is limited both by intraguild predation and infrequent feeding in field situations, noting that in the field, spiders consume prey at rates below their maximum feeding capacity. However, findings of the current study give an indication of the relative predatory capabilities of the three spider groups. The relative abundance of each type of spider should also be taken into account when considering potential impact on pests. For instance, although Clubionidae/Miturgidae have been found to be more voracious than the smaller theridiids in laboratory trials, typically no more than one spider was found per plant, whereas Theridiidae were more numerous. In summary, the ubiquitous presence of spiders in the crops surveyed during this study, and their demonstrated predatory capability, indicate that they could be an important factor limiting lepidopteran pest populations in *Brassica* crops. However, field trials are required to assess the impact of these predators in commercial cropping situations.

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