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A comparison of naturally growing vegetation vs. border-planted companion plants for sustaining parasitoids in pomegranate orchards

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ABSTRACT

Diversification of vegetation within and around agricultural habitats is an effective strategy to support populations of natural enemies of crops' pests. Such diversification can be achieved by conservation of natural vegetation that develops spontaneously around the plots, as well as by active introduction of companion plants to the crop. In this study we compared these two approaches in pomegranate orchards in Mediterranean climate. First, we evaluated ten candidate companion plant species for their potential to attract parasitoids of pomegranate pests. We then planted a combination of the two leading species – celery and Syrian oregano – along the perimeter of five orchards. In five additional, paired orchards, no plants were added. Arthropods were sampled from added and naturally growing companion plants throughout the pomegranate fruit growth season. Parasitoids were the most common natural enemies in our samples, and their overall abundance was similar in both treatments. Pest levels did not differ between treatments either. However, the distribution of some parasitoids (*Neochrysocharis* and *Telenomus*) and pests (leafhoppers and dipteran leafminers) within the orchards was affected by the margin vegetation type: these insects were more abundant in the margins than in the centers of the orchards with companion plants (suggesting a role as trap plants), whereas the opposite was observed in orchards with natural vegetation. We conclude that introduction of companion plants and conservation of local natural vegetation were equally effective in sustaining parasitoid numbers and diversity, but that planting attracted some parasitoids away from the orchards towards their margins. This possibly provides these natural enemies with a refuge from agricultural disturbances, but might reduce their contribution to pest control.

1. Introduction

Conservation biological control uses habitat management interventions to enhance the abundance and activity of natural enemies in agricultural plots. This is often done by active introduction of non-crop plant species (planted companion plants), or by preserving the wild vegetation that develops spontaneously inside and around the plot (wild companion plants). Both strategies increase the number of companion plant species in the agroecosystem. This, in turn, often boosts the diversity and richness of the natural enemy community (Landis et al., 2000; Parolin et al., 2012). Companion plants provide various resources to natural enemies including pollen, nectar, alternative hosts, hibernation or aestivation sites and shelter (see Landis et al., 2000; Naranjo et al., 2015; Parolin et al., 2012; Parker et al., 2013 for reviews). Although conserving naturally-growing wild companion plants in agricultural plots is relatively easy, farmers often prefer specific planted companion plants. One reason could be that spontaneously-growing wild species are usually considered to be weed pests or reservoirs of crop viruses. Another reason is lack of research: some commercially-grown planted species have been evaluated as companion plants for several crops and habitats, while wild plants native to the tested areas are rarely evaluated (Fiedler et al., 2008).

Despite the potential benefits, the overall effects of non-crop plants on the arthropod community and the agricultural crops may vary greatly due to the complex nature of such systems, and may depend, among other factors, on the composition of plant species. For example, some companion plants may provide resources not only to natural enemies but also to pest species, which can lead to increased herbivore populations and crop damage (Landis et al., 2000; Lavandero et al., 2006). Companion species can also act as trap plants, affecting the spatial distribution of herbivores and natural enemies within the plot even if their total numbers remain unchanged (Cook et al., 2006; Hokkanen 1991). For example, plants can be used to pull pests away from the agricultural field (Khan et al., 1997), or, on the other hand,

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plants can be planted at the borders of the field in order to attract natural enemies from the surrounding area (Parker et al., 2013). Theoretically, this method could, unintentionally, decrease the numbers of natural enemies inside the plot and lower the efficiency of biological control agents.

These considerations make it difficult to predict whether introduction of planted border- companion plants, or conservation of spontaneously-growing wild companion plants, would be the preferable method to enhance natural enemies in a given agro-ecosystem. Here, we addressed this issue in pomegranate (*Punica granatum* L. (Lythraceae)) orchards in a Mediterranean climate. The pomegranate season in Israel begins with flowering in April and ends with the harvest in October. Locally important pests of pomegranate include several lepidopteran and hemipteran species, while the composition of natural enemies in the orchards is generally unknown. We focused on parasitoids since we found them to be the most abundant group of natural enemies in the sampled areas. Based on this crop-specific information, we asked how the identity of companion plants (planted vs. wild) along the border of the orchards affects the abundance, diversity and spatial distribution of natural enemies and pests. To address this question we evaluated candidate planted companion plants for pomegranate and selected two species for further study. In the following season we conducted a planting experiment to compare the arthropod assemblages on the selected planted companion plants to those on the wild vegetation growing within and around matched orchards.

2. Materials and methods

2.1. Plant evaluation experiment (2013): selecting planted companion plants

2.1.1. Selection of candidate plants

Ten plant species were selected for screening as potential planted companion plants: basil *Ocimum basilicum* L. (Lamiaceae), celery *Apium graveolens* L. (Apiaceae), common yarrow *Achillea millefolium* L. (Asteraceae), false yellowhead *Dittrichia viscosa* L. (Asteraceae), french marigold *Tagetes patula* L. (Asteraceae), gaura *Oenothera lindheimeri* (Engelmann et A. Gray) (Onagraceae), rosemary *Rosmarinus officinalis* L. (Lamiaceae), Syrian oregano *Origanum syriacum* L. (Lamiaceae), vitex *Vitex agnus-castus* L. (Lamiaceae) and white petunia *Petunia x hybrida* (Vilm) (Solanaceae). In accordance with criteria outlined by Fiedler et al. (2008), the evaluated species are of different life-forms (see Table 1), and their flowers produce pollen and/or nectar as potential resources for natural enemies. These species were expected to thrive and flower during the hot and dry pomegranate season, and are readily available in local nurseries.

2.1.2. Study area and experimental design

The experiment was conducted in a 4-ha, 6-year-old pomegranate orchard (cv 'Wonderful') in the Hefer Valley in central Israel (32°22'48N, 34°55'58E). The climate in the sampled area during the pomegranate fruit growth season (May-October) is characterized by high temperatures (average ± SD: 24.9 ± 4.3°C, max: 38.3°C, min: 7.7°C) and RH (70.4 ± 15.5%), with no rainfall. Ninety plants (9 each of the ten candidate species) were planted individually in a randomized block design: 60 plants were placed at the ends of the orchard's 30 tree rows (one plant at each end of each row), and 30 additional plants were planted along a dirt path that ran perpendicular to the rows in the center of the orchard. The distance between adjacent plant individuals was 6 m. The test plants were introduced into the orchard in May 2013, and were fertilized and drip-irrigated throughout the season along with the pomegranate trees.

2.1.3. Arthropod sampling

Arthropods were sampled using a Vortis Insect Suction Sampler (Burkard Manufacturing Co. Ltd., Rickmansworth, UK). Each plant was suction-sampled individually for 15 s, and samples were preserved in 75% ethanol until sorted. Sampling was conducted monthly from May through September 2013.

2.1.4. Arthropod classification

We identified the collected arthropods to a minimum level of order. Hemiptera and Diptera were identified to suborder or family levels. Parasitic Hymenoptera, the most abundant group of natural enemies collected (see below), were identified to genus and morphospecies based on Goulet and Huber, 1993; Grissell et al., 1997, (Superfamily Chalcidoidea key); Hayat, 1983; Huber et al., 2009; Masner, 1976, 1980; Noyes, 2003; Pinto, 1997, 2006; Pricop, 2013; Schauff et al., 1997; Shaw and Huddleston, 1991; Ulrich, 2006; Woolley, 1997. These sources also provided information on host range.

2.1.5. Analysis of arthropod abundance

The abundance of parasitic Hymenoptera and potential pomegranate pests (Aleyrodidae, Aphididae, Auchenorrhyncha, Lepidoptera and Pseudococcidae) on the test plants was calculated by averaging the numbers collected from the individual plants of each species on each sampling date. This generated one data point per plant species for each sampling date. The effects of plant species on pest and parasitoid richness was analyzed using Kruskal Wallis tests, since the data did not conform to the assumptions of ANOVA even after transformations. All analyses were performed using SPSS 12.0 (IBM SPSS statistics, Chicago, IL, USA).

2.1.6. Selection of suitable companion plants for pomegranate orchards

The suitability of plants for use in margin planting in pomegranate orchards was estimated according to the abundance of potential pests and natural enemies found on them throughout the season, as detailed in the Results section. Two plant species, celery and Syrian oregano, were eventually selected for the planting experiment, which was conducted in the following season.

Table 1
Plant species evaluated in the first year of the study.

Family	Species name	Common name	Life-form	Native?
Asteraceae	*Achillea millefolium* L.	Common yarrow	Perennial Forb	No
	Dittrichia viscosa L.	False Yellowhead	Perennial shrub	Yes
	Tagetes patula L.	French marigold	Annual Forb	No
Apiaceae	*Apium graveolens* L.	Celery	Biennial Forb	Yes
Lamiaceae	*Ocimum basilicum* L.	Basil ('Magic Mountain')	Perennial shrub	No
	Origanum syriacum L.	Origanum	Perennial shrub	Yes
	Rosemarinus officinalis L.	Rosemary	Perennial shrub	No
Onagraceae	*Oenothera lindheimeri* Engelmann et A. Gray	Gaura	Perennial Forb	No
Solanaceae	*Petunia x hybrida* Vilm	White petunia	Perennial Forb	No
Verbenaceae	*Vitex agnus-castus* L.	Vitex	Perennial shrub	Yes

2.2. Planting experiment (2014): comparing the selected planted companion plants with wild companion plants

2.2.1. Study plots and experimental design

Planting of companion plants was compared to wild vegetation in five pairs of pomegranate orchards cv 'Wonderful' (see Supplementary material Table S1, for details on the study sites). Tested plants were placed in one orchard (the "planting orchard") of each pair. The companion plants were planted individually at both ends of each tree row forming a continuous row at the ends of the tree rows. Plants were planted during the first week of June 2014, after removal of wild plants. A "border planting"-like pattern (see Map S2) (Parker et al., 2013) was used, since it is most compatible with the common agricultural practices and constraints in pomegranate orchards in Israel. It allows economical irrigation and fertilization of the non-crop plants, required during the hot and dry summer, using the drip-irrigation system installed for the fruit trees (water is an expensive input in Israel, thus irrigation costs of rows of dense flower strips would make the crop non-profitable). Moreover, this planting pattern does not interfere with the cultivating routine and herbicide applications within the orchard. Wild plants were removed, if present, from the surrounding area within a 1 m radius of the planted individuals once a month after planting. Celery attracted higher numbers of parasitoids than Syrian oregano in the plant evaluation experiment (see Results). Therefore, to maximize the effect of the added plants celery was planted in higher numbers (a 3:1 ratio). Since Syrian oregano attracted a very different assemblage of parasitoids this plant was also added (see more details about the decision rationale in the results). In the paired orchards (the "non-planting orchards"), wild plants were not removed throughout the season. All orchards were treated with pesticides (see Table S1 for details) and herbicides according to the directions of an extension specialist, except for the planted companion plants that were not treated with herbicides. This means that the natural vegetation sampled in the non-planting orchard was destroyed several times during the season. Nonetheless, some plants were always present at the ends of tree rows due to re-sprouting and new germination, and they were sampled. The orchards within each pair were of comparable sizes and were managed by a single grower using similar agricultural practices.

2.2.2. Arthropod sampling

Arthropods were sampled monthly from May (the first sampling was conducted before planting) to October using a vacuum sampler as described above. On each sampling date, 14 plants from the perimeter of the orchard (celery and Syrian oregano in the planting orchards, wild companion plants in the non-planting orchards) were sampled. In addition, wild plants were sampled along six 3-m transects in the interior of all orchards, between the rows. This was done to assess the effects of the non-crop vegetation along the orchards' borders on the abundance of parasitoids within the orchards. All of the wild plants sampled were identified and recorded. Adult lepidopterans were rarely captured by suction sampling (see Results). Therefore, the population densities of the principal lepidopteran pests of pomegranate were monitored using two methods: 1) males of the honeydew moth, *Cryptoblabes gnidiella* (Mill.) (Pyralidae) and the false codling moth *Thaumatotibia leucotreta* (Meyrick) (Tortricidae) were monitored using species-specific sex pheromone traps ("Unitraps" "Shacham, Givat Ada" LTD, Israel). Three traps per species were placed in two diagonal corners and at the center of each orchard, and were monitored and refreshed monthly. The distances between traps depended on orchard size, 2) because the sex pheromone of the pomegranate playboy *Deudorix livia* (Klug) (Lycaenidae) has not been isolated yet, it was the only pest monitored actively by examining 100–200 fruits monthly. The number of pomegranates examined was adjusted to achieve a uniform sampling effort of 110 fruits per hectare. Infested fruits were incubated at room temperature to verify the identity of the emerging pests or parasitoids. Another lepidopteran pest, the European grapevine moth *Lobesia botrana* (Den. and Schiff.) (Tortricidae) was not monitored, since the study orchards were managed with mating disruption pheromones, which reduced the populations of this pest below economic threshold. Hemipteran pests such as *Aphis* spp. (Aphididae), *Empoasca* spp. (Cicadellidae), *Siphoninus phillyreae* (Haliday) (Aleyrodidae) and *Planococcus* spp. (Pseudococcidae) were monitored using the suction samples.

2.2.3. Analysis of arthropod diversity and abundance

The average abundance of the following arthropod guilds was calculated by averaging the numbers collected in each orchard across sampling dates: all natural enemies combined, parasitoids, all pests combined, lepidopterans from pheromone traps and from monitoring of infested fruit. Paired-sample *t*-tests were performed to compare planting and non-planting orchards. If the data did not conform to the assumptions of *t*-tests even after transformation, Wilcoxon Signed test were performed. Parasitoid diversity was analyzed using the Simpson's species diversity index. Analyses were performed using SPSS 12.0.

2.2.4. Comparing arthropod abundance between orchard center and margins

We compared the abundance of the most common parasitoid genera (*Anagrus, Encarsia, Neochrysocharis, Trichogramma and Telenomus*) and their potential hosts (*Empoasca* leafhoppers, *Bemisia* whiteflies, leaf-mining Diptera and Lepidoptera respectively) inside and around both planting and non-planting orchards using Linear Mixed models. We conducted the analyses in R (R Core Team, 2013) using the function "lmer" within the library 'lmer4′ (Bates et al., 2015). The models included arthropod abundance as the dependent variable. The type of margin vegetation (planted/non-planted), the location within the orchard (center/margins) and their interaction were defined as the fixed factors. Orchard number was treated as a random-intercept variable (the subject variable), to take into account the repeated-measures design of the experiment. Study site was defined as a second random-intercept variable, to account for the pairing of orchards within each site. The locations of the lepidopteran pests in the orchards were not monitored and therefore their spatial distribution could not be related to the non-crop plant composition.

3. Results

3.1. Plant evaluation experiment (2013): selecting planted companion plants

3.1.1. Abundance of potential pests

Pest numbers varied among plant species (Kruskal Wallis test: $\chi^2_9 = 28.2$, $p < 0.001$). Out of the 15,033 arthropods sampled, lepidopterans were collected in negligible numbers from all plants with the highest numbers found on basil (Supplementary material, Table S3). Other potential pomegranate pests included Aleyrodidae, Aphididae and Cicadellidae. The greatest numbers of Aleyrodidae, mostly *Bemisia tabaci* (Gennadius), were collected from basil, marigold, and yarrow (means ± standard errors: 28.7 ± 13.3, 7.3 ± 3.0, and 7.1 ± 3.1 individuals per plant over the season, respectively). Aphididae were most abundant on celery (8.7 ± 1.4 per plant over the season), and were common mostly early in the season.

3.1.2. Abundance of potential natural enemies

Parasitic Hymenoptera were the most common natural enemies on all plant species (n = 1010), followed by Araneae (Table S3). Of the parasitic wasps collected across all plant species, the superfamily Chalcidoidea was the most abundant, followed by Platygastroidea and Ichneumonoidea. Parasitoid numbers varied among plant species (Kruskal Wallis test: $\chi^2_9 = 26.5$, $p = 0.002$) with celery harboring the highest numbers (Fig. 1). The main groups found on each plant species are detailed in Table 2.

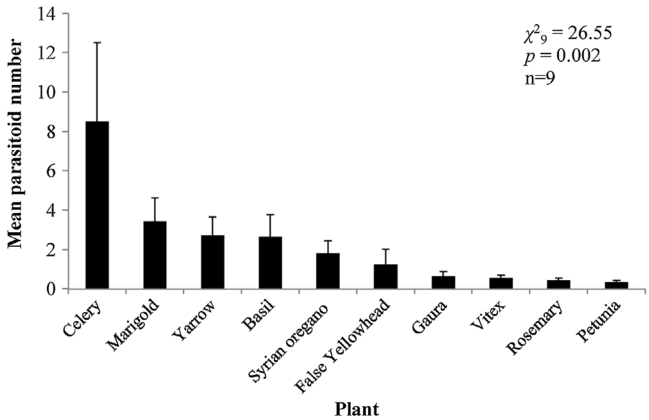

Fig. 1. Numbers (means ± SE of the five sampling dates) of parasitic Hymenoptera collected per plant per sampling date from the companion plants planted in the pomegranate orchard during the first year of the study. The data were analyzed using the Kruskal-Wallis test.

3.1.3. Selection of companion plants

Celery and Syrian oregano were selected for the planting experiment, based on the following considerations: 1. of all the tested plants, celery was associated with the greatest number of parasitoids potentially attacking pomegranate pests. It had the largest number of *Trichogramma* (spp) individuals (many of which parasitize Lepidoptera eggs (Pinto, 2006)), and high numbers of the leafhopper parasitoids *Anagrus* (spp.) individuals (Cerutti et al., 1990). 2. Syrian oregano was unique in harboring large numbers of *Telenomus* (spp.) individuals, some of which are egg parasitoids of lepidopterans (Masner, 1976). 3. The combination of celery and Syrian oregano provided a complementary assemblage of parasitoids that can potentially attack pomegranate pests.

3.2. Planting experiment (2014): comparing selected planted companion plants with wild vegetation

3.2.1. Numbers and diversity of arthropods collected

A total of 66,059 arthropods were suction sampled during the course of the season in all the orchards combined. Natural enemies included various species of predatory bugs, beetles, lacewings, thrips and spiders, but parasitic wasps were the dominant group, with 4317 individuals (78% of all natural enemies) belonging to 192 morphospecies. The numbers of natural enemies collected from vegetation around the plots were similar in planting and non-planting orchards. The statistical results for this comparison between orchards, and for those reported in the following paragraphs, are summarized in Table 3.

3.2.2. Abundance of potential pests

The total numbers of pests sampled did not differ between the treatments. The numbers of lepidopteran pests collected by vacuuming and in pheromone traps, and the proportions of Lepidoptera-infested fruit did not differ between the treatments either.

3.2.3. Abundance, diversity and distribution of parasitoids

The abundance of parasitoids varied greatly among pairs of orchards (the range was 81–413 parasitoid individuals per orchard throughout the season), but did not differ overall between the treatments (Table 3). Different plant species were dominated by different parasitoid genera (Table 4). Parasitoid diversity was similar in planting and non-plating orchards, whether the samples were taken at the margins or in the center of the orchard. Parasitoid diversity was, however, higher in the margins of the orchards than in their centers (Mean ± SE Simpson diversity index values for the 10 orchards: margins: 5.5 ± 0.4, center: 3.9 ± 0.4; Wilcoxon Signed test: $Z = -0.3$, $p = 0.007$). The distribution of some arthropods within the orchards was affected by the marginal vegetation. Leaf-mining Diptera, their parasitoids of the genus *Neochrysocharis*, the leafhopper *Empoasca* and parasitoids of the genus *Telenomus* were more abundant in the plot margins than in the centers of the planting orchards. They showed the opposite pattern in the non-planting orchards (Fig. 2. Statistics for the interaction between non-crop vegetation type and middle/margin location are: Leafminers: $F_{1,986} = 30.5$, $p < 0.0001$; *Empoasca:* $F_{1,986} = 15.2$, $p = 0.0001$; *Neochrysocharis*: $F_{1,946} = 12.8$, $p = 0.0003$ and *Telenomus*: $F_{1,946} = 10.1$, $p = 0.0016$). Other arthropods, on the other hand, differed in abundance between center and margin in both types of orchards: 1. all leafhopper parasitoids pooled together, as well as *Anagrus* (spp.) individuals, the dominant genus in this parasitoid guild, were more abundant at the orchards' margins than at the centers, regardless of treatment ($F_{1,946} = 6.4$, $p = 0.0101$; $F_{1,986} = 3.9$, $p = 0.0491$, respectively); 2. the numbers of *Encarsia* (spp.) individuals and their principal host *B. tabaci* were higher in the centers of the orchards than along the margins, irrespective of treatment ($F_{1,946} = 37.9$, $p < 0.0001$; $F_{1,986} = 47.4$, $p < 0.0001$, respectively). The abundance of the other tested arthropods indicated no preference to center or margin ($p \geq 0.05$).

Table 2
Total number of parasitic Hymenoptera families, the most abundant genus within each family and its main hosts, collected in samples from the companion plant species in 2013 (9 plant individuals per species, each sampled five times during the season). "Others" refers to families that represented no more than 3% of the total parasitoid sample (Bethylidae, Ceraphronidae, Chalcididae, Diapriidae, Encyrtidae, Eupelmidae, Eurytomidae, Figitidae, Magaspilidae and Pteromalidae).

Plant (total parasitoid number)	Parasitic Hymenoptera families individuals sampled						
	Aphelinidae	Braconidae	Eulophidae	Mymaridae	Platygastridae	Trichogrammatidae	Others
Basil (120)	35	6	14	12	22	23	4
Celery (383)	8	30	133	152	20	25	15
False Yellowhead (56)	4	4	33	4	6	1	4
Gaura (29)	4	0	1	9	5	5	5
Marigold (155)	18	15	60	46	6	5	5
Syrian oregano (82)	8	2	6	9	52	5	5
Petunia(8)	0	0	1	4	1	1	1
Rosemary (20)	9	1	0	3	0	3	3
Vitex (26)	0	0	4	8	5	6	4
Yarrow (123)	35	15	26	19	16	7	5
Most abundant genus	*Encarsia* (89%)	*Opius* (88%)	*Neochrysocharis* (53%)	*Anagrus* (66%)	*Telenomus* (81%)	*Trichogramma* (66%)	
Primary hosts	Diaspididae and Aleyrodidae	Diptera	Coleoptera, Diptera, Hymenoptera and Lepidoptera	Cicadellidae and Delphacidae	Lepidoptera	Lepidoptera	
References	Woolley (1997)	Shaw and Huddleston (1991)	Schauff et al. (1997)	Huber et al. (2009)	Masner (1976)	Pinto (2006)	

Table 3
Statistical analyses' results of various measured parameters in the planting experiment (2014) − Comparing selected companion plants with wild vegetation. In samples collected from vegetation around the plots, we compared companion plants vs. wild vegetation in the paired orchards.

Comparisons between planting and non-planting orchards	Statistical test result
The total numbers of pests (lepidopterans and homopterans) collected from vegetation around the plots	Paired samples *t*-test: t_4 = 0.973, p = 0.386
Lepidopteran pests from vegetation around the plots in suction samples	Paired samples *t*-test: t_4 = 1.47, p = 0.216
Numbers of male *C. gnidiella* moths in pheromone traps	Wilcoxon Signed test: Z = −0.135, p = 0.893
Numbers of male *T. leucotreta* moths in pheromone traps	Wilcoxon Signed test: Z = −0.135, p = 0.893
Proportion of damaged fruit by the butterfly *D. livia*	Paired samples *t*-test: t_4 = −1.45, p = 0.221
Numbers of natural enemies collected from vegetation around the plots	Paired samples *t*-test: t_4 = 0.277, p = 0.796
Abundance of parasitoids collected from vegetation around the plots	Paired samples *t*-test: t_4 = 0.248, p = 0.816
Parasitoid Simpson's species diversity index collected from vegetation around the plots	Paired samples *t*-test: t_4 = 0.05, p = 0.96
Parasitoid Simpson's species diversity index collected from vegetation in the middle of the plots	Paired samples *t*-test: t_4 = 0.49, p = 0.65

Table 4
Dominant parasitoid genera sampled from the margin plants in the 2014 season. Only plant species recorded in more than six samples are shown.

Plant species (number of plants sampled)	Dominant parasitoid genera (≥15%)	% (of total parasitoids from this plant)	Total number of parasitoids sampled on the plant
Beggar ticks - *Bidens pilosa* (9)	*Neochrysocharis*	45	65
	Encarsia	15	
Flax-leaf fleabane - *Conyza bonariensis* (80)	*Telenomus*	50	204
	Tumidiclava	16	
Matted sandmat - *Euphorbia serpens* (18)	*Telenomus*	52	82
	Tumidiclava	17	
	Encarsia	16	
Prickly lettuce - *Lactuca serriola* (9)	*Trichogramma*	28	25
Knotgrass - *Paspalum distichum* (15)	*Anagrus*	19	21
	Neochrysocharis	19	
Common purslane - *Portulaca oleracea* (20)	*Telenomus*	39	46
Syrian mesquite - *Prosopis farcta* (51)	*Telenomus*	27	118
Hooked bristlegrass - *Setaria verticillata* (14)	*Anagrus*	26	81
Common sowthistle - *Sonchus oleraceus* (14)	*Eretmocerus*	37	30
	Encarsia	33	
Black pigweed - *Trianthema portulacastrum* (26)	*Aphelinoidea*	18	182
	Trichogramma	19	
Goat's-head - *Tribulus terrestris* (16)	*Aphelinoidea*	56	80
[a]Celery - *Apium graveolens* (245)	*Neochrysocharis*	18	815
	Anagrus	15	
[a]Syrian oregano - *Origanum syriacum* (103)	*Telenomus*	56	401

[a] companion plants that were planted in 5 out of 10 orchards.

4. Discussion

This study encompasses a process of selecting and testing the effectiveness of planted companion plants, as compared to wild companion plants, for supporting parasitoids in pomegranate orchards under Mediterranean climate conditions. Of the initial ten evaluated planted companion plant species, celery and Syrian oregano were chosen as the leading candidates because they attracted the highest number of complementary potential parasitoids of pomegranate pests.

During the second year of the study, when Syrian oregano and celery were planted in the margins of pomegranate orchards, we found no significant differences in overall pest abundance, parasitoid abundance and parasitoid diversity between the planted companion plants and the wild companion plants growing within and around the orchards. Moreover, some of the plants growing wild in the orchards attracted very similar compositions of parasitoids (and often in higher numbers) to those sampled from celery and Syrian oregano (Table 4). Planting of companion plants did, however, affect the spatial distribution of some pests and parasitoids within the orchards (Fig. 2). The planted celery and origanum may have acted as trap plants and possibly attracted leafhoppers away from the center of the orchard. This alone could be beneficial in reducing leafhopper populations inside the orchards. Parasitoids attacking leafhoppers were also more abundant at the margins than at the centers of all plots (probably following their hosts), potentially reducing leafhopper populations and subsequent influx from the margins inside. Similarly to our finding, Khan et al. (1997) reported that the lepidopteran stem-borers pests *Busseola fusca* (Noctuidae) and *Chilo partellus* (Pyralidae) were not only attracted away from the main crop by trap plants but were also parasitized more often on the added plants. The added plants in our study potentially acted as trap plants for another herbivore guild − leafmining Diptera, and for their parasitoids of the genus *Neochrysocharis.* Leafminers are not pests of pomegranate, but using celery and Syrian oregano as trap plants for leafminers could be tested for other crop types. On the other hand, the added plants also had a potentially negative effect on the distribution of beneficial insects, as *Telenomus* parasitoids were more abundant on the margin plants than at the center of the planting orchards. It is possible that the added plants provided the parasitoids with a refuge from agricultural disturbances such as repeated insecticide applications (Table S1), but this might also minimize their potential biocontrol activity. To maintain *Telenomus* species, many of which are lepidopteran parasitoids (Masner, 1976), inside the orchards it is therefore better to

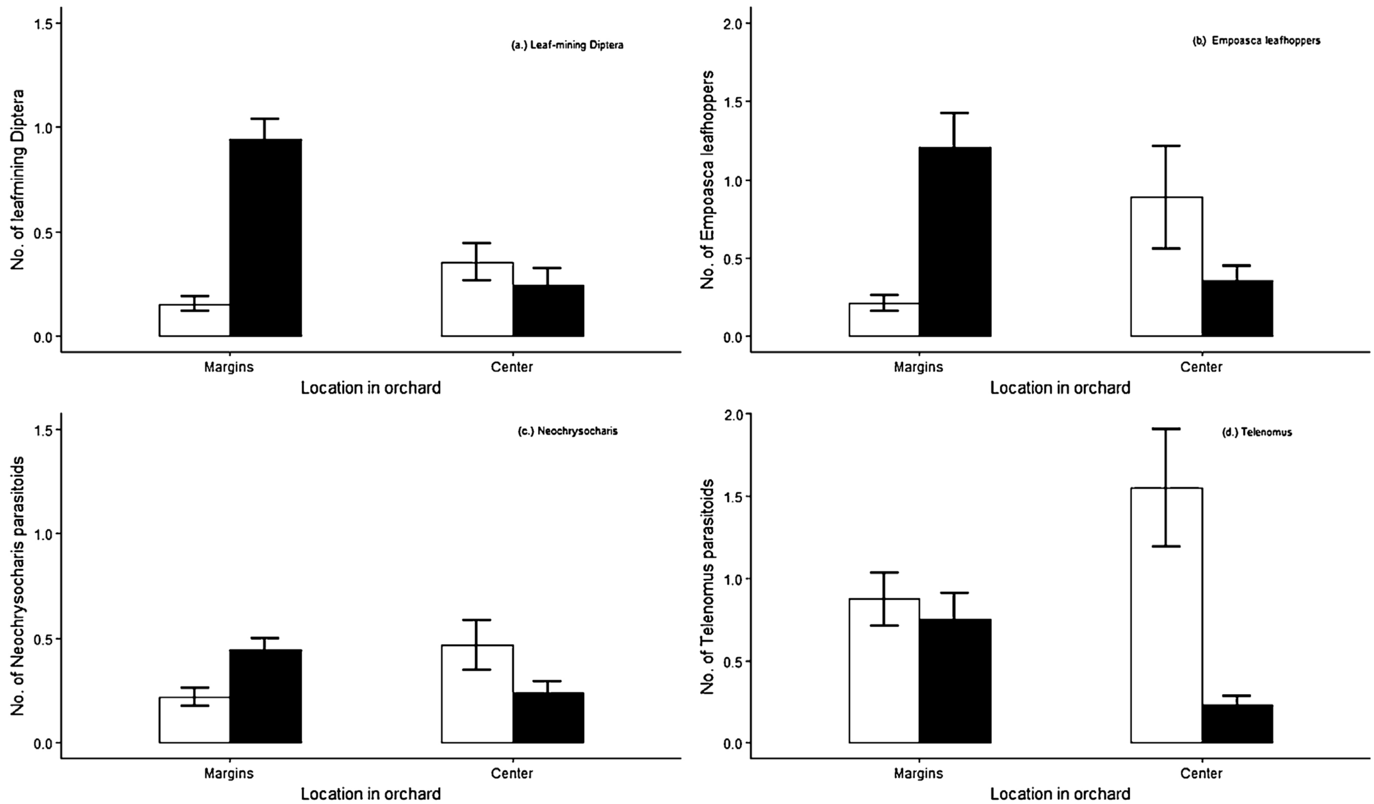

Fig. 2. Mean ± SE abundance of (a) Leaf-mining Diptera, (b) the leafhopper *Empoasca* (c) *Neochrysocharis* (leafminer parasitoids) and (d) *Telenomus* (parasitoids of Lepidoptera), along the margins and in the centers of non-planting (white bars) or planting (black bars) orchards (n = 5 orchards in each treatment). Data were averaged over all sampling dates. The interaction between vegetation type (planted/natural) and location within the orchard (center/margins) significantly affected insect abundance in all cases.

preserve the natural vegetation inside the plots or to add plants at the center of the orchards. These results illustrate that the identity of the non-crop plants at the orchards' margins may influence the distribution of some pests and parasitoids even if their total numbers are not affected. Several studies (Derocles et al., 2014; Feng et al., 2017) found that parasitoids rarely move from non-crop vegetation in the margins to the crop, indicating that non-crop vegetation should be preserved inside the crop field and not in the margins. These results agree with ours and emphasize the potentially negative influence of border planting.

The planted companion plants attracted some parasitoids from the orchard to the margins, and did not increase their overall abundance, compared with wild companion plants. In contrast, for other parasitoids, neither abundance nor spatial distribution were affected by the type of non-crop plants at the orchard margins. This variability is compatible with our previous findings that different parasitoid species respond differently to host- versus plant-related variables (Kishinevsky et al., 2016). According to our results, spontaneously growing natural vegetation may supply resources to natural enemies as effectively as plants that are actively added to the plot. This idea was previously suggested by Altieri and Koohafkan (2004) and was proven useful both in the laboratory and in field studies of aphid parasitoids (Araj and Wratten, 2015; Skirvin et al., 2011). Our findings lend further support to the proposal that native plants may be equal to, or even superior to introduced species as companion plants (Fiedler et al., 2008). According to this view, plants that grow in and around the plot, including those considered noxious should be screened, conserved and enhanced as resources for natural enemies before introducing companion plants from other habitats. Conservation of local plants may be achieved through reduction in herbicide sprays, a potentially simple and cost-effective management strategy. Preservation of wild vegetation is also simpler for the farmers than buying and planting specific plants. Moreover, wild plants are potentially more adapted to the environment of the orchard and could better survive there than added alien plants.

To conclude, our study highlights the complexity of selecting and employing non-crop plants for conservation of beneficial arthropods. We advocate inclusion of local natural vegetation, which grow spontaneously in and around the agricultural plots, in the evaluation process. Comparison of parasitism rates of pests in planting vs. non-planting orchards was not attempted here, but is an obvious next step for future studies.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2017.05.034.

References

Altieri, M.A., Koohafkan, P., 2004. Globally important ingenious agricultural heritage systems (GIAHS): extent, significance, and implications for development. In: Proceedings of the Second International Workshop and Steering Committee Meeting for the Globally Important Agricultural Heritage Systems (GIAHS) Project. FAO, Rome, Italy. pp. 7–9.
Araj, S.E., Wratten, S.D., 2015. Comparing existing natural vegetation and commonly used insectary plants as floral resources for a parasitoid. Biol. Control 81, 15–20.
Bates, D., Maechler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Software 67, 1–48.

Cerutti, F., Baumgärtner, J., Delucchi, V., 1990. Research on the grapevine ecosystem in Tessin: III. Biology and mortality factors affecting *Empoasca vitis* Goethe (Homoptera, Cicadellidae, Typhlocybinae). Mitteilungen der Schweizerischen Entomologischen Gesellschaft 63, 43–54.

Cook, S.M., Khan, Z.R., Pickett, J.A., 2006. The use of push-pull strategies in integrated pest management. Annu. Rev. Entomol. 52, 375–400.

Derocles, S.A.P., Ralec, A.L., Besson, M.M., Maret, M., Walton, A., Evans, D.M., Plantegenest, M., 2014. Molecular analysis reveals high compartmentalization in aphid–primary parasitoid networks and low parasitoid sharing between crop and noncrop habitats. Mol. Ecol. 23, 3900–3911.

Feng, Y., Kravchuk, O., Sandhu, H., Wratten, S.D., Keller, M.A., 2017. The activities of generalist parasitoids can be segregated between crop and adjacent non-crop habitats. J Pest Sci 90, 275. http://dx.doi.org/10.1007/s10340-016-0775-2.

Fiedler, A.K., Landis, D.A., Wratten, S.D., 2008. Maximizing ecosystem services from conservation biological control: the role of habitat management. Biol. Control 45, 254–271.

Goulet, H., Huber, J.T., 1993. Hymenoptera of the World: an Identification Guide to Families. Research Branch, Agriculture Canada.

Grissell, E., Schauff, M., Gibson, G., Huber, J., Woolley, J., 1997. Annotated Keys to the Genera of Nearctic Chalcidoidea (Hymenoptera). NRC Research Presspp. 709–725.

Hayat, M., 1983. The genera of Aphelinidae (Hymenoptera) of the world. Syst. Entomol. 8, 63–102.

Hokkanen, H.M.T., 1991. Trap cropping in pest management. Annu. Rev. Entomol. 36, 119–138.

Huber, J.T., Viggiani, G., Jesu, R., 2009. Order hymenoptera, family Mymaridae. Arthropod Fauna of the UAE 2, 270–297.

Khan, Z.R., Ampong-Nyarko, K., Chiliswa, P., Hassanali, A., Kimani, S., Lwande, W., Overholt, W.A., Picketta, J.A., Smart, L.E., Woodcock, C.M., 1997. Intercropping increases parasitism of pests. Nature 388, 631–632 (no. 6643).

Kishinevsky, M., Keasar, T., Bar-Massada, A., 2017. Parasitoid abundance on plants: effects of host abundance, plant species, and plant flowering state. Arthropod-Plant Interact 11, 155–161.

Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu. Rev. Entomol. 45, 175–201.

Lavandero, B., Wratten, S.D., Didham, R.K., Gurr, G., 2006. Increasing floral diversity for selective enhancement of biological control agents: a double-edged sward? Basic Appl. Ecol. 7, 236–243.

Masner, L., 1976. Revisionary notes and keys to world genera of Scelionidae (Hymenoptera: proctotrupoidea). Mem. Entomol. Soc. Can. 108, 1–87.

Masner, L., 1980. Key to genera of Scelionidae of the Holarctic region, with descriptions of new genera and species (Hymenoptera: proctotrupoidea). Mem. Entomol. Soc. Can. 112, 1–54.

Naranjo, S.E., Ellsworth, P.C., Frisvold, G.B., 2015. Economic value of biological control in integrated pest management of managed plant systems. Annu. Rev. Entomol. 60, 621–645.

Noyes, J.S., 2003. Universal Chalcidoidea Database. (http://www.nhm.ac.uk/research-curation/research/projects/chalcidoids/. Access date: 2013).

Parker, J.E., Snyder, W.E., Hamilton, G.C., Rodriguez-Saona, C., 2013. Companion planting and insect pest control. In: Soloneski, S., Larramendy, M. (Eds.), Weed and Pest Control Conventional and New Challenges. InTech, Rijeka, pp. 1–30.

Parolin, P., Bresch, C., Desneux, N., Brun, R., Bout, A., Boll, R., Poncet, C., 2012. Secondary plants used in biological control: a review. Int. J. Pest. Manag. 58, 91–100.

Pinto, J.D., 1997. Trichogrammatidae. Annotated Keys to the Genera of Nearctic Chalcidoidea (Hymenoptera). NRC Research Presspp. 726–752.

Pinto, J.D., 2006. A review of the new world genera of trichogrammatidae (Hymenoptera). J. Hymenoptera Res. 15, 38–163.

Pricop, E., 2013. Identification Key to European Genera of the Mymaridae (Hymenoptera: Chalcidoidea), with Additional Notes 5. ELBA Biofluxpp. 69–81.

R Core Team, 2013. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna Austria.

Schauff, M.E., LaSalle, J., Coote, L.D., 1997. Eulophidae. Annotated Keys to the Genera of Nearctic Chalcidoidea (Hymenoptera). NRC Research Presspp. 327–429.

Shaw, M., Huddleston, T., 1991. Classification and biology of braconid wasps. Handbooks for the Identification of British Insects 7. pp. 126.

Skirvin, D.J., Kravar-Garde, L., Reynolds, K., Wright, C., Mead, A., 2011. The effect of within-crop habitat manipulations on the conservation biological control of aphids in field-grown lettuce. Bull. Entomol. Res. 101, 623–631.

Ulrich, W., 2006. Body weight distributions of European hymenoptera. Oikos 114, 518–528.

Woolley, J.B., 1997. Aphelinidae. Annotated Keys to the Genera of Nearctic Chalcidoidea (Hymenoptera) 794. NRC Research Presspp. 134–150.