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Do primary and secondary host plants affect aphid- parasitoid interactions in fruit orchards?

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Research Paper

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Abstract

The aim of this study was to investigate how the primary (PHP) and secondary host plants (SHP) in the fruit orchards affect the interactions of aphids and their parasitoids in northwest Turkey during spring and summer 2020 and 2021. In total, 67 tritrophic aphid–parasitoid-host plant interactions, including new association records for Europe and Turkey, were obtained from 16 parasitoid species from the subfamily Aphidiinae (Hymenoptera: Braconidae) reared from 25 aphid species (Hemiptera: Aphididae) on 22 PHP and SHP in the fruit orchards. Also, we evaluated the effect of the PHP and SHP on the parasitoids, aphids and their interactions. We revealed that the species richness and the values of the biodiversity indices of the parasitoids and aphids were significantly higher on the SHP than the PHP. Similarly, the aphid–parasitoid interactions on the SHP showed greater diversity than the PHP. The results of this study clearly show that the interactions of parasitoids and aphids in the fruit orchards were more diverse on the SHP compared to the PHP.

Introduction

Aphids (Hemiptera: Aphididae) are one of the most destructive agricultural pests which feed on a large number of crops such as fruits, vegetables, cereals, forest and ornamental plants, sucking up plant sap and secreting honeydew. In addition, aphids can transmit more than 270 phytopathogenic viruses to many agricultural crops (Katis *et al.*, 2007; Dedryver *et al.*, 2010). From more than 5000 known aphid species, about 450 cause damage to crop plants and among them, approximately 100 species are considered key pests for agricultural crops worldwide (Blackman and Eastop, 2007). In fruit orchards, aphids can cause damage such as a reduction of fruit size, deformation of fruit shape, premature fruit fall, leaf rolling, shoot twisting, chlorosis, sooty mould development on honeydew and decreased carbohydrates reserves (Van Emden *et al.*, 1969; Filajdić *et al.*, 1995; Hullé *et al.*, 2006; Dedryver *et al.*, 2010; Zvereva *et al.*, 2010). Also, it was demonstrated that the sucking of carbohydrates in host plants by sap-sucking insects including aphids led to falling carbohydrate reserves, which negatively affects the growth of the plant (Smith and Schowalter, 2001). In the 21st century, chemical control involving the use of pesticides is still one of the most common control methods against many insect pests in agricultural production (Hashemi and Damalas, 2010; Simon-Delso *et al.*, 2015). Considering the negative effects of pesticides used against aphid pests, such as pesticide resistance (Margaritopoulos *et al.*, 2007; Wang *et al.*, 2007; Ahmad and Akhtar, 2013; Ulusoy *et al.*, 2018) and the negative effects of pests (Rogers *et al.*, 2011; Sabahi *et al.*, 2011; Cheng *et al.*, 2021), the importance of alternative control methods, including biological control, is increasing day by day.

Many natural enemies such as predators from the family Coccinellidae (Coleoptera), Syrphidae (Diptera) and Chrysopidae (Neuroptera), parasitoids from the subfamily Aphidiinae (Braconidae) and the family Aphelinidae (Hymenoptera) and pathogens contribute to the success of the biological control of aphids (Völkl *et al.*, 2007). Of these, parasitoid species such as *Aphidius matricariae* (Haliday) and *Lysiphlebus testaceipes* (Cresson) (Hymenoptera: Aphidiinae) can cause significant parasitism rates on some aphid species and they are successfully used in the biological control of aphid pests on agricultural crops (Boivin *et al.*, 2012; Rezaei *et al.*, 2019; Zhang *et al.*, 2020). Parasitoid species belonging to the subfamily Aphidiinae are solitary koinobiont endoparasitoids which lay a single egg into the soft body of aphids (Völkl and Mackauer, 2000) and the most significant and investigated groups due to their crucial role in biological control as the natural enemies of aphid pests. The subfamily is represented by more than 500 species belonging to 38 genera, about half of which belong to the group of strict specialists which attack only one aphid species, and most of them are distributed in the Holarctic region (Žikić *et al.*, 2017). Furthermore, Aphidiinae parasitoids are important agents used in the biological control of aphid pests,

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and have a rich biodiversity in orchards (Carroll and Hoyt, 1986; Monteiro *et al*., 2004; Kavallieratos *et al*., 2008; Rakhshani, 2012; Alhmedi *et al*., 2018; Aparicio *et al*., 2019).

The diversity of host plant species may have an effect on the population densities and species richness of aphids and parasitiods in both agricultural and non-agricultural areas (Petermann *et al*., 2010). The introduction of some companion plant species or the conservation of native vegetation have been effective in sustaining the diversity and density of parasitoids. In addition, such vegetation can attract some parasitoids in and around orchards or fields, and it also provides them with important refuge areas (Tomanović *et al*., 2009; Kishinevsky *et al*., 2017; Aparicio *et al*., 2019). Also, it is known that many host plant species in non-agricultural areas can provide reservoirs for both aphids and their parasitoids (Barczak *et al*., 2014; Kök, 2021). For example, *Arundo donax* L. (Poaceae), the summer host of *Hyalopterus pruni* (Geoffroy) (Hemiptera: Aphididae), which is a serious pest for plums and apricots, hosts some pest aphids as well as providing a reservoir for many natural enemies, including many parasitoid species (Askar *et al*., 2013). On the other hand, the host plant diversity and presence of floral resources play an important role on the some biological features and biological control effectiveness of aphid parasitoids. Jado *et al*. (2019) revealed that the number of mummified aphids parasited by *Aphidius colemani* Viereck (Hymenoptera: Aphidiinae) on *Fagopyrum esculentum* Moench (Polygonaceae) flowers was the highest of all treatments. Also, the laboratory and field experiments proved that the presence of sugar resources and the proximity to floral resources significantly increased fecundity of parasitoids and their rates of parasitism on aphids (Tylianakis *et al*., 2004). From agricultural fields, fruit orchards containing primary (PHP; fruit trees) and secondary host plants (SHP; herbaceous plants) can provide significant data on the interactions of aphids with heteroecious life cycles, which migrate between different host plants during the year. As an example of this, Alhmedi *et al*. (2018) reported that non-crop plants (herbaceous or woody plants) showed a significant richness compared to fruit crop plants in terms of many biodiversity values, especially the species richness of both aphids and parasitoids.

In light of the above, we deemed that a detailed investigation of the interactions of aphids–parasitoids on PHP and SHP would contribute to the more effective use and success of parasitoids in biological control studies in fruit orchards. Consequently, the aim of this study was to discover the effect of PHP and SHP on the interactions and biodiversity of aphids and their parasitoids in fruit orchards.

Methods

Sampling site

Our sampling area consists of about 30 fruit orchards, each of which has an average size of 5–7 decares and is cultivated with one or mixed fruit varieties, in Bayramiç, Biga, Ezine, Lâpseki and the central districts of the Çanakkale province in the northwestern part of Mediterranean Turkey. The fruit production is carried out in an area of more than 160 thousand decares of fruit orchards in the Çanakkale province, located in the southern Marmara region of Turkey (TUIK, 2021). In the region, fruit varieties such as quince, apple, cherry and peach are widely produced. In our sampling area, in addition to that of fruit, olive, vegetable and grain production is also carried out, and these agricultural areas are intertwined with each other. There are also many non-agricultural areas with non-crop plants around the orchards.

Sampling and identification of parasitoids, host aphids and host plants

In order to discover the effect of PHP and SHP on the biodiversity of parasitoids and aphids, field sampling was carried out from numerous fruit trees such as quince, apple, cherry, peach, plum and herbaceous host plants in and around the fruit orchards in Çanakkale. The samplings were conducted by visiting as many orchards as possible once a week in the spring-autumn and every two weeks in the summer during 2020 and 2021. For fruit tree sampling, aphid-infested trees were selected to represent the orchards homogeneously. For herbaceous plants sampling, all herbaceous plants in and around (up to about five meters) the fruit orchards were visually checked and their aphid-infested ones were selected.

For the sampling of the parasitoid species, mummified aphids were collected from a number of host plants which included fruit trees as well as herbaceous host plants in and around the fruit orchards. The parasitoid specimens collected were brought to the laboratory in boxes and kept in colonies on the host plants in plastic bottles and kept in the laboratory conditions (22.5°C, 65% humidity, 16:8 L:D photoperiod) until the parasitoid emergence. Parasitoids were morphologically identified by the second author using several keys (Tomanović *et al*., 2007; 2014; 2021; Kos *et al*., 2012).

For the sampling of host aphid species of parasitoids, apterous and alate host aphids from the colonies on the infested fruit trees and herbaceous host plants were transferred with a soft brush (#00) into Eppendorf tubes containing 70% ethyl alcohol and then brought to the laboratory for slide-preparation and identification. The preparation of the host aphid specimens was conducted according to the method of Hille Ris Lambers (1950). The identification of the host aphids was done by the first author using a LEICA DM 2500 microscope with a mounted HD camera and LAS software (version 4.1) according to Blackman and Eastop (2006, 2022). Also, the current taxonomic status and names of the identified host aphids were given as in Favret (2021). The specimens of the identified parasitoids were deposited in the Institute of Zoology, University of Belgrade, Faculty of Biology, Serbia, while those of the host aphids were deposited in the Department of Plant Protection, Faculty of Agriculture, Çanakkale Onsekiz Mart University, Turkey.

The PHP and SHP samples determined to be aphid hosts were prepared as herbarium specimens for identification. The host plants associated with aphids were identified by the third author.

Data analysis

In order to visualize the structural patterns of the tritrophic host-parasitoid- host-aphid plant network on the PHP and SHP in the fruit orchards, tripartite interaction graphs were constructed on the basis of the data on the parasitoid, aphid, and host plant relative abundances using the *plotweb2* function in the *bipartite* package. To calculate the biodiversity values of the parasitoids and aphids separately on the PHP and SHP the *diversityresult* function in the *BiodiversityR* package (Kindt and Kindt, 2019) was used, while the *networklevel* function in the *bipartite* package was used to reveal the biodiversity values, such as

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Table 1. Parasitoid, host aphid and host plant species determined in the fruit orchards

Code	Parasitoid species	Code	Host aphid species	Code	Host plant species
P1	*Aphidius colemani* Viereck	A1	*Acyrthosiphon pisum* (Harris)	H1	*Anthemis* sp. (Asteraceae)
P2	*Aphidius ervi* Haliday	A2	*Aphis acetosae* Linnaeus	H2	Unknown 1 (Asteraceae)
P3	*Aphidius funebris* Mackauer	A3	*Aphis ballotae* Passerini	H3	*Ballota* sp. (Lamiaceae)
P4	*Aphidius matricariae* Haliday	A4	*Aphis craccae* Linnaeus	H4	*Capsella rubella* (Brassicaceae)
P5	*Aphidius* sp. 1	A5	*Aphis craccivora* Koch	H5	*Chenopodium album* (Amaranthaceae)
P6	*Aphidius* sp. 2	A6	*Aphis fabae* Scopoli	H6	*Chenopodium* sp. (Amaranthaceae)
P7	*Binodoxys acalephae* (Marshall)	A7	*Aphis gossypii* Glover	H7	*Cydonia oblonga* (Rosaceae)
P8	*Binodoxys angelicae* (Haliday)	A8	*Aphis lamiorum* (Börner)	H8	*Cynoglossum creticum* (Boraginaceae)
P9	*Diaeretiella rapae* (Curtis)	A9	*Aphis pomi* De Geer	H9	*Diplotaxis* sp. (Brassicaceae)
P10	*Ephedrus persicae* Froggatt	A10	*Aphis rumicis* Linnaeus	H10	*Lamium purpureum* (Lamiaceae)
P11	*Lipolexis gracilis* Forster	A11	*Aphis solanella* Theobald	H11	*Malus domestica* (Rosaceae)
P12	*Lysiphlebus fabarum* (Marshall)	A12	*Aphis spiraecola* Patch	H12	*Malus* sp. (Rosaceae)
P13	*Lysiphlebus testaceipes* (Cresson)	A13	*Aulacorthum solani* (Kaltenbach)	H13	Unknown 2 (Poaceae)
P14	*Monoctonus cerasi* (Marshall)	A14	*Brachycaudus amygdalinus* (Schouteden)	H14	*Prunus armeniaca* (Rosaceae)
P15	*Praon abjectum* Haliday	A15	*Brachycaudus helichrysi* (Kaltenbach)	H15	*Prunus avium* (Rosaceae)
P16	*Praon volucre* (Haliday)	A16	*Dysaphis plantaginea* (Passerini)	H16	*Prunus domestica* (Rosaceae)
		A17	*Hyperomyzus lactucae* (Linnaeus)	H17	*Prunus dulcis* (Rosaceae)
		A18	*Lipaphis pseudobrassicae* (Davis)	H18	*Prunus persica* (Rosaceae)
		A19	*Myzus cerasi* (Fabricius)	H19	*Ranunculus muricatus* (Ranunculaceae)
		A20	*Myzus persicae* (Sulzer)	H20	*Rumex* sp. (Polygonaceae)
		A21	*Myzus* sp.	H21	*Sonchus* sp. (Asteraceae)
		A22	*Ovatus insitus* (Walker)	H22	*Vicia* sp. (Leguminosae)
		A23	*Phorodon humuli* (Schrank)		
		A24	Unknown 1		
		A25	*Uroleucon sonchi* (Linnaeus)		

connectance, links per species, Shannon diversity of interactions, interaction evenness and H2 of the interactions of the parasitoid–aphid and host-aphid- plants on the PHP and SHP. Also, the nestedness *(N)* and modularity *(M)* were calculated for the interaction networks of the parasitoid–aphid and aphid-host plants on the PHP and SHP using the *nested* and *metaComputeModules* functions of in the *bipartite* R software package of (version 3.6.1) (Dormann *et al*., 2014; R Core Team, 2022).

Results

In this study, 16 parasitoid species belonging to eight genera from the subfamily Aphidiinae emerged from 25 aphid species on 22 host plants (table 1). A total of 67 tritrophic parasitoid–aphid-host plant interactions, including new records for Europe and Turkey, were determined from the fruit orchards. Of these, 30 aphid–parasitoid interactions were determined on the primary hosts and 37 interactions on the secondary hosts (figs 1 and 2).

From the aphid–parasitoid- interactions presented in our study, the associations *Monoctonus cerasi* (Marshall) (Code: P14; table 1)- *Aphis spiraecola* Patch (A12) on the host plant *Cydonia oblonga* (Rosaceae) (H7), *Binodoxys angelicae* (Haliday) (P8)- *Brachycaudus amygdalinus* (Schouteden) (A14) on the host plant *Prunus dulcis* (Rosaceae) (H17), *A. colemani* Viereck (P1)- *Aphis ballotae* Passerini (A3) on the host plant *Ballota* sp. (Lamiaceae) (H3), and *L. testaceipes* (Cresson) (P13)- *Aphis lamiorum* (Börner) (A8) on the host plant *Lamium purpureum* (Lamiaceae) (H10) are new to Europe. Also, the associations *Mo. cerasi* (P14)-*A. spiraecola* (A12) on the host plant *C. oblonga* (H7), *A. colemani* (P1), *Bi. angelicae* (P8) and *Ly. testaceipes* (P13)- *Dysaphis plantaginea* (Passerini) (A16) on the host plant *Malus domestica* (Rosaceae) (H11), *A. colemani* (P1), *Aphidius ervi* Haliday (P2), *Diaeretiella rapae* (Curtis) (P9) and *Praon abjectum* Haliday (P15)- *Myzus cerasi* (Fabricius) (A19) on the host plant *Prunus avium* (Rosaceae) (H15), *Bi. angelicae* (P8)-*Br. amygdalinus* (A14) on the host plant *P. dulcis* (H17), *A. colemani* (P1)-*A. ballotae* (A3) on the host plant *Ballota* sp. (H3), *Ly. testaceipes* (P13)-*A. lamiorum* (A8) on the host plant *L. purpureum* (H10), *Ly. testaceipes* (P13)- *Aphis solanella* Theobald (A11) on the host plant *Ranunculus muricatus* (Ranunculaceae) (H19), *Ly. testaceipes* (P13) and *Bi. angelicae* (P8)- *Aphis acetosae* Linnaeus (A2) on

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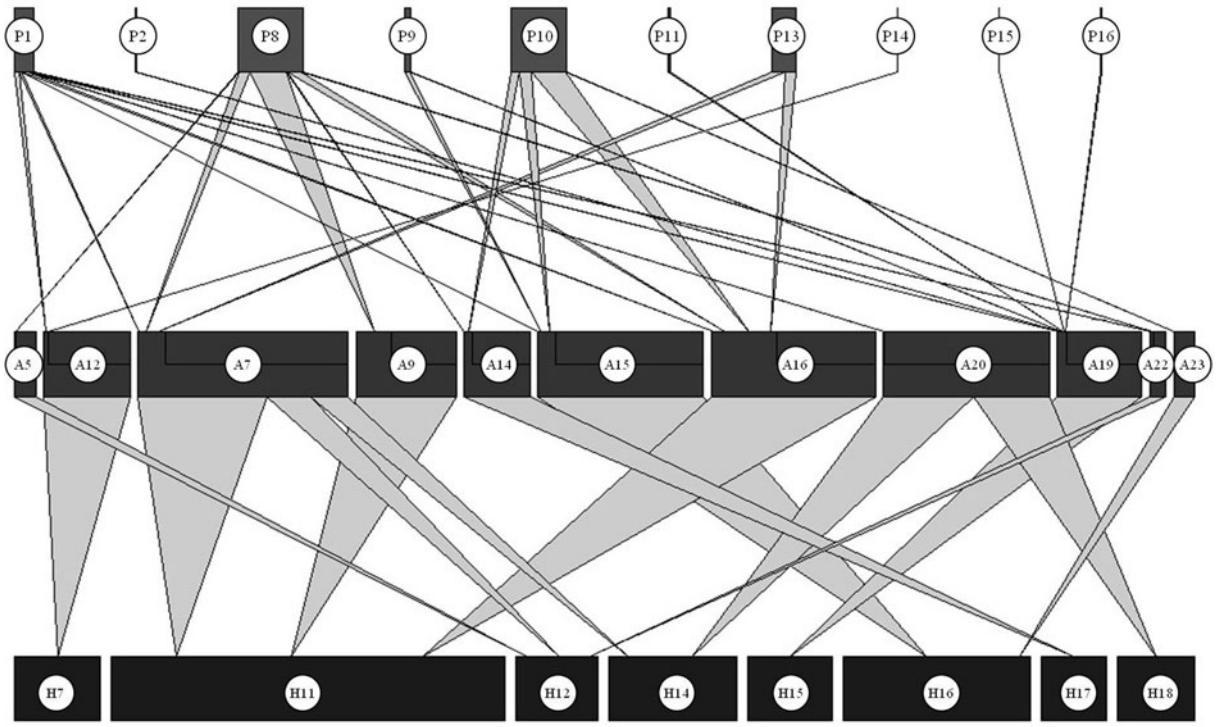


Fig. 1. The quantitative tripartite network of the interactions between parasitoids (top), aphids (middle), and PHP (bottom) in the fruit orchards in northwestern Turkey. The black bars represent the abundance of the species and the gray bars represent the interactions (the width of the bars indicates the intensity of the interactions).

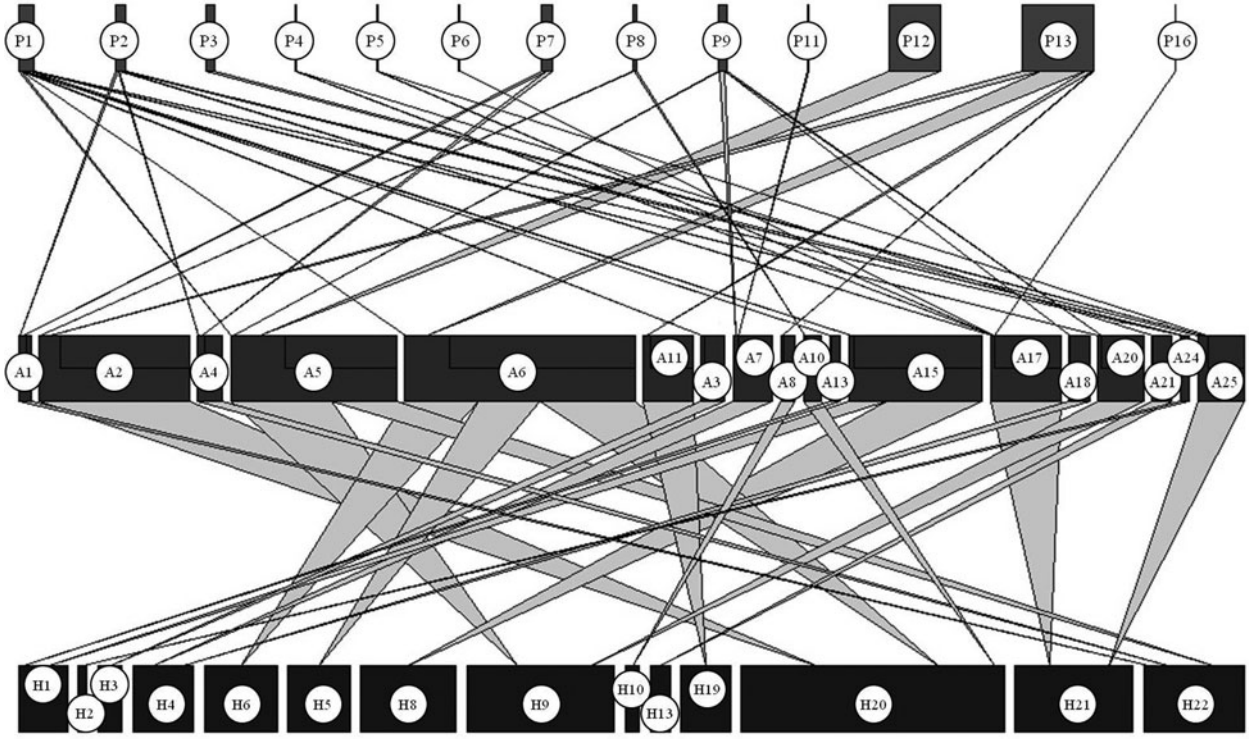


Fig. 2. The quantitative tripartite network of the interactions between parasitoids (top), aphids (middle), and SHP (bottom) in the fruit orchards in northwestern Turkey. The black bars represent the abundance of the species and the gray bars represent the interactions (the width of the bars indicates the intensity of the interactions).

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the host plant *Rumex* sp. (Polygonaceae) (H20), and *A. ervi* (P2)-*Hyperomyzus lactucae* (Linnaeus) (A17) on the host plant *Sonchus* sp. (Asteraceae) (H21) were recorded for the first time in Turkey.

On the PHP, i.e. the fruit trees, *A. colemani* (P1) reared from seven aphid species and *Bi. angelicae* (P8) reared from six aphid species were the most common parasitoids. On the other hand, *A. ervi* (P2), *Lipolexis gracilis* Forster (P11), *Mo. cerasi* (P14), *P. abjectum* (P15) and *Praon volucre* (Haliday) (P16) visited only one aphid species on the primary hosts. From the aphids, *Aphis pomi* De Geer (A9) parasitized by six parasitoid species and *Dy. plantaginea* (A16) parasitized by four parasitoid species were the most preferred aphid species by parasitoids. From the PHP, *M. domestica* (H11) with eight parasitoid–aphid interactions and *P. avium* (H15) with six parasitoid–aphid interactions were the plants which hosted the most parasitoid–aphid interactions (fig. 1). On the secondary hosts, i.e. the herbaceous plants in and around the orchards, *A. colemani* (P1) reared from seven aphid species, and *A. ervi* (P2), *Di. rapae* (P9) and *Ly. testaceipes* (P13) reared from four aphid species were the most common parasitoids. However, *Aphidius* sp. (P5, P6), *Li. gracilis* (P11) and *P. volucre* (P16) targeted only one aphid species on the secondary hosts. As for aphids, *H. lactucae* (A17) parasitized by five parasitoid species, and *Aphis craccivora* Koch (A5) and *Uroleucon sonchi* (Linnaeus) (A25) parasitized by three parasitoid species were the most preferred aphid species by parasitoids. From the SHP, *Sonchus* sp. (H21) with eight parasitoid–aphid interactions and *Rumex* sp. (H20) with six parasitoid–aphid interactions were the plants which hosted the most parasitoid–aphid interactions (fig. 2).

In terms of the species richness of the parasitoids and aphids on the PHP and SHP in the fruit orchards, our results showed that the parasitoids on the aphids feeding on the SHP have higher species richness than the parasitoids on the aphids feeding on the PHP ($S = 10$ on PHP, $S = 13$ on SHP). Similarly, the species richness of the host aphids on the secondary hosts was higher than that of the aphids on the primary hosts ($S = 11$ on PHP, $S = 18$ on SHP). On the other hand, the abundance of both the parasitoids and aphids was higher on the primary hosts than on the secondary hosts ($N = 414$ on the PHP and $N = 280$ on the SHP for the parasitoids; $N = 2574$ on the PHP and $N = 2120$ on the SHP) (table 2). The Berger-Parker, Simpson and Shannon indices used to investigate the diversity of the parasitoids on the host aphids feeding on the PHP and SHP in the fruit orchards showed that the parasitoid biodiversity was higher on the secondary than on the PHP ($D_{BP} = 0.370$, $D_{SI} = 0.733$, $H' = 1.533$ on the PHP; $D_{BP} = 0.361$, $D_{SI} = 0.798$, $H' = 1.918$ on the SHP) (table 2). In parallel with this result, it was also determined that the aphids feeding on the secondary hosts had higher diversity than the primary hosts ($D_{BP} = 0.191$, $D_{SI} = 0.871$, $H' = 2.167$ on the PHP; $D_{BP} = 0.177$, $D_{SI} = 0.918$, $H' = 2.705$ on the SHP) (table 2). Also, the Shannon Evenness values proved that both the parasitoid and aphid diversity on the SHP were higher due to their high evenness values in the fruit orchards ($E = 0.463$ on the PHP and $E = 0.524$ on the SHP for the parasitoids; $E = 0.794$ on the PHP and $E = 0.831$ on the SHP for the aphids) (table 2).

Considering both the parasitoid biodiversity on the aphid species and the aphid biodiversity on the host plant species, the highest parasitoid biodiversity on the primary hosts was determined on *My. cerasi* (A19) ($D_{SI} = 0.776$, $H' = 1.600$), followed by *Dy. plantaginea* (A16) ($D_{SI} = 0.644$, $H' = 1.194$) and *Aphis gossypii* Glover (A7) ($D_{SI} = 0.574$, $H' = 0.930$). On the other hand, the highest parasitoid biodiversity on the secondary hosts was recorded for *H. lactucae* (A17) ($D_{SI} = 0.716$, $H' = 1.427$), followed by an unknown aphid species ($D_{SI} = 0.494$, $H' = 0.687$), and *Myzus persicae* (Sulzer) (A20) ($D_{SI} = 0.490$, $H' = 0.683$). The highest values of aphid biodiversity on the primary hosts were determined on *M. domestica* (H11) ($D_{SI} = 0.653$, $H' = 1.079$), *Malus* sp. (H12) ($D_{SI} = 0.605$, $H' = 1.011$) and *Prunus armeniaca* (Rosaceae) (H14) ($D_{SI} = 0.418$, $H' = 0.609$), while the highest values of aphid biodiversity on the secondary hosts were recorded for *Rumex* sp. (H20) ($D_{SI} = 0.644$, $H' = 1.061$), *Vicia* sp. (Leguminosae) (H22) ($D_{SI} = 0.628$, $H' = 1.043$) and *Anthemis* sp. (Asteraceae) (H1) ($D_{SI} = 0.500$, $H' = 0.693$) (fig. 3).

As for the biodiversity of the interactions of the aphid–parasitoid- network and the aphid-host plants network on the PHP and SHP in the fruit orchards, the connectance values for both the parasitoids and aphids were lower in the SHP compared to the PHP (table 3). Similarly, the number of links per species for both parasitoids and aphids was noticeably lower in the secondary than in the PHP. The calculated nestedness and modularity values clearly showed that the networks on the PHP were more nested than those on the SHP ($N = 17.960$ for the aphid–parasitoids- on the PHP and $N = 35.945$ for the aphids on the PHP; $N = 16.846$ for the aphid–parasitoids- on the SHP and $N = 21.791$ for the aphids on the SHP). In addition, the networks on the SHP were more modular than those on the PHP ($M = 0.430$ for the aphid–parasitoids- on the PHP and $M = 0.698$ for the aphids on the PHP; $M = 0.687$ for the aphid–parasitoids- on the SHP and $M = 0.816$ for the aphids on the SHP) (table 3). Considering the biodiversity of the interactions between the networks, it was determined that the interactions in both the networks of the aphid–parasitoids- and aphid-host plants on the secondary hosts ($H' = 2.792$ and $H' = 3.043$, respectively) showed higher diversity than those on the primary hosts ($H' = 2.569$ and $H' = 2.449$, respectively). It was also determined that the values of interaction evenness of the networks on both the PHP and SHP were partially similar. On the other hand, the

Table 2. The biodiversity of the parasitoids and aphids on the PHP and SHP in the fruit orchards

			Biodiversity indices			
	Richness (*S*)	Abundance (*N*)	Berger-Parker (D_{BP})	Simpson (D_{SI})	Shannon (*H'*)	Evenness (*E*)
Parasitoids of aphids on the PHP	10	414	0.370	0.733	1.533	0.463
Parasitoids of aphids on the SHP	13	280	0.361	0.798	1.918	0.524
Aphids on the PHP	11	2574	0.191	0.871	2.167	0.794
Aphids on the SHP	18	2120	0.177	0.918	2.705	0.831

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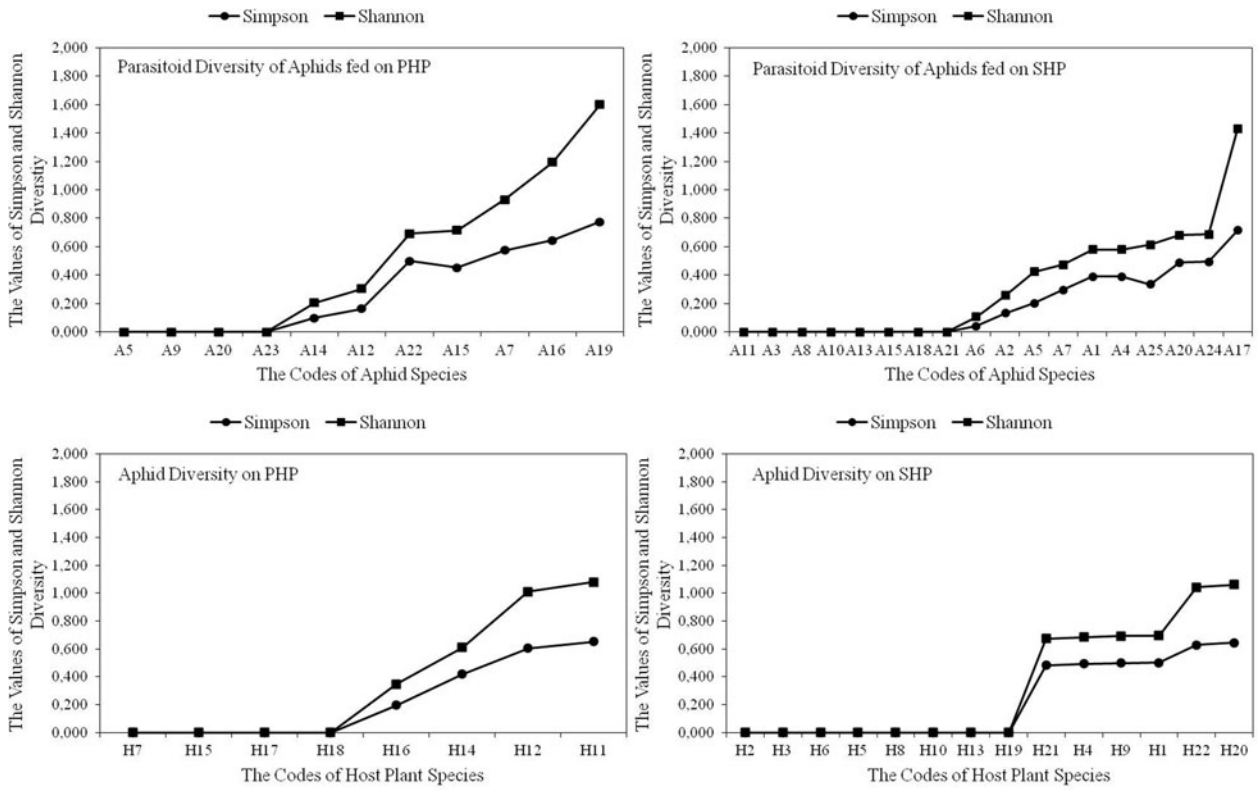


Fig. 3. The biodiversity of the parasitoids of aphids and the aphids on the PHP and SHP in the fruit orchards.

H2 values calculated at the network-level showed that for both the networks of aphid–parasitoids- and aphid-host plants, the specialization was significantly higher in the secondary than in the PHP (table 3).

Discussion

The diversity of the host plant species directly or indirectly affects the aphid–parasitoid interactions, the density and richness of the species, the parasitism rate, as well as the host preference and host specificity of parasitoids (Kavallieratos *et al.*, 2002; Petermann *et al.*, 2010; Albittar *et al.*, 2016; Monticelli *et al.*, 2021; Peñalver-Cruz *et al.*, 2021; Ward *et al.*, 2021). Considering that about 10% of aphids are heteroecious, spending the winter, spring and autumn on primary hosts including trees or shrubs and then migrating to secondary hosts including herbaceous plants during the summer (Blackman and Eastop, 2022), it can be concluded that both the PHP and SHP influence the diversity of aphids and their parasitoids (Kök and Kasap, 2022).

Studies show that aphid–parasitoid interactions are highly diverse on fruit trees and herbaceous host plants in and around fruit orchards worldwide (Tizado and Nunez Perez, 1998; Kavallieratos *et al.*, 2002; Aslan and Karaca, 2005; Rakhshani, 2012; Aslan, 2015; Alhmedi *et al.*, 2018). In our study, 16 parasitoid species associated with 25 aphid species reported in the fruit orchards from Turkey contributed significantly to the diversity of the aphid–parasitoid interactions. Also, the four new aphid–parasitoid-interactions for Europe and 15 new interactions for Turkey presented in our study revealed both the positive effect of the PHP -SHP on the diversity of the aphid–parasitoid- interactions in the fruit orchards and the contribution of these interactions to biological control strategies in the fruit orchards. As a result, it is believed that these new interactions will make an important contribution to the biological control of fruit aphid pests by using parasitoids.

On the other hand, an important perspective obtained from our data is that when exploring the parasitoid diversity of aphids with heteroecious life cycles in agricultural areas, the PHP and the SHP should be examined separately. In this regard, Alhmedi *et al.*

Table 3. The biodiversity of the interactions of the aphid–parasitoids- and aphid-host plants in the fruit orchards.

Networks	Connectance	Links per species	Nestedness *(N)*	Modularity *(M)*	Shannon diversity of interactions *(H')*	Interaction evenness *(E)*	H2
Network of aphid–parasitoid-on the PHP	0.236	1.238	17.960	0.430	2.569	0.547	0.516
Network of aphid–parasitoid-on the SHP	0.141	1.065	16.846	0.687	2.792	0.512	0.842
Network of aphid-PHP	0.159	0.737	35.945	0.698	2.449	0.547	0.919
Network of aphid-SHP	0.087	0.688	21.791	0.816	3.043	0.550	0.917

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(2018) revealed that the species richness of aphids and parasitoids on non-crop herbaceous plants and non-crop shrub and tree plants was higher than on fruit crop plants in fruit orchards, and they also reported the highest connectance on fruit crop plants (0.114 and 0.122 in 2014 and 2015, respectively) compared to non-crop herbaceous plants (0.074 and 0.063 in 2014 and 2015, respectively) and non-crop shrub and tree plants (0.070 and 0.083 in 2014 and 2015, respectively). The results of our study, which support the findings above, showed that the species richness for both parasitoids (10 on PHP and 13 on SHP) and aphids (11 on the PHP and 18 on the SHP) was highest on the SHP in the fruit orchards. Also, the connectance of parasitoids (0.236 on PHP and 0.141 on SHP) and aphids (0.159 on PHP and 0.087 on SHP) was lowest on the SHP. The results of our study and that of Alhmedi *et al.* (2018) show that the level of specialization of parasitoids and aphids was relatively higher on the SHP in the fruit orchards. Also, the fact that the number of links per species was lower on the SHP for both the parasitoids and aphids in our study supports this result (table 3). One of the results of our study, referring to the specialization of both the parasitoids and aphids, was that the interactions of the aphid–parasitoids– and the aphid–host plants were more nested on the PHP than the SHP. On the other hand, these interactions were more modular on the SHP than on the PHP. In support of this, a study including the results on the interactions of ant-aphids and aphid-host plants in different habitats by Kök *et al.* (2022) revealed that the specialization of ants and aphids in the uncultivated areas was higher than in cultivated and urban areas.

In light of the above, it should be taken into account that host selection of specialist and generalist parasitoids is associated with the interactions between aphids and their host plants in different habitats (Stilmant *et al.*, 2008). In this regard, the result we obtained in our study is that the diversity of both the parasitoids and aphids separately, and the aphid–parasitoid interactions in the fruit orchards were higher on the SHP with greater richness of aphids and host plants compared to the PHP (tables 2, 3). On the other hand, the diversity of aphid–parasitoid/predator- interactions on SHP including flowers, herbaceous plants, shrubs and trees in and around agricultural areas are important in terms of their contribution to the biological control of pest aphids (Gontijo *et al.*, 2013; Aparicio *et al.*, 2019, 2021). Also, many non-crop SHP in these areas are reservoirs for parasitoid species (Tomanovic *et al.*, 2006, 2009; Kavallieratos *et al.*, 2008; Barczak *et al.*, 2014; Satar *et al.*, 2021; Kök and Kasap, 2022). On this basis, the results of our study showed that some parasitoid species such as *A. colemani* (P1), *L. testaceipes* (P13) and *P. volucre* (P16), important biological control agents and classified as polyphagous parasitoids (Kavallieratos *et al.*, 2004; Boivin *et al.*, 2012; Žikić *et al.*, 2017), emerged from both the PHP and SHP in the fruit orchards. As a result, it is considered that parasitoid species can survive using aphids on the SHP during the summer without the populations of aphids feeding on the primary host fruit trees during spring. Also, it is generally known that landscape heterogeneity in agricultural areas with a higher proportion and diversity of non-crop habitats positively effects aphid–parasitoid complexity and their species richness, and supports the biological control of pest aphids (Plećaš *et al.*, 2014; Letourneau *et al.*, 2015), although some results do not support such findings (Hawro *et al.*, 2015). In parallel with this, we argue that the higher diversity and complexity of aphid–parasitoid-interactions on the non-crop SHP, which we presented in our study, support this result, although there was no result showing the higher biological effectiveness of the parasitoids.

Also, we believe that the results of our study provided basic data on the use of flowering plants on the interactions of aphid–parasitoids and their possibilities for use in the biological control of fruit pest aphids. Furthermore, it is known that conservation biological control in agricultural areas can be supported by the use of non-crop plant species and preserving the wild vegetation including self-sowing plants in and around the agricultural areas. Moreover, many studies conducted in fruit orchards proved that some flowering plants, namely secondary herbaceous hosts, promote the increased effectiveness of parasitoids on pest aphids (Gontijo *et al.*, 2013; Kishinevsky *et al.*, 2017; Aparicio *et al.*, 2021). Based on our results, it can be interpreted that *Sonchus* sp. (H21) with eight aphid–parasitoid- interactions, *Rumex* sp. (H20) with six aphid–parasitoid- interactions, and *Vicia* sp. (H22) with five aphid–parasitoid- interactions have significant potential for use as companion plants in agricultural areas such as fruit orchards.

In view of the fact that fruit pest aphids have a heteroecious life cycle using both the PHP and SHP, it is believed that a better understanding of the biodiversity of the parasitoids and aphids on these host plants and their interactions will provide important basic data for the biological control of aphids using parasitoids in fruit orchards. Also, the new interactions between the parasitoids and aphids in the fruit orchards of both Europe and Turkey presented in this study will contribute to the development of biological control strategies and a more meaningful interpretation of aphid–parasitoid- interactions. Our study clearly showed that the biodiversity of the parasitoids, aphids and aphid–parasitoid-interactions in the fruit orchards were more diverse on the SHP than the PHP. Based on our results, we suggest that the interactions of aphid–parasitoids- on both PHP and SHP in agricultural areas should be examined in more detail.

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Author contributions. All authors contributed to the study conception and design. ŞK collected the aphid, parasitoid and host plant samples, identified the aphid specimens, performed all statistical analyses, wrote the manuscript; ŽT performed the identification of parasitoid specimens; EK performed the identification of host plant species; İK collected the aphid, parasitoid and host plant samples. All authors reviewed and approved the final manuscript.

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