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Effect of host plant species and temperature on the development and survival of the plant bug *Closterotomus trivialis* (Costa) (Hemiptera: Miridae)

Argyro Kalaitzaki · Adel Amara · Sofia Dervisoglou · Dionyssios Perdikis · Despina Tzobanoglou · Ioannis Koufakis · Antonios Tsagkarakis

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Abstract Nymphal development, mortality and adult longevity of the plant bug *Closterotomus trivialis* were studied on two of its major crops (*Olea europaea* L. cv. 'Koroneiki' and *Citrus sinensis* L. cv. 'Washington Navel') and four non-crop host plants (*Mercurialis annua* L., *Urtica urens* L., *Parietaria diffusa* M. et K. and *Sinapis alba* L.) under laboratory conditions (15, 20, 24 and 27 °C ± 0.5%; 60 ± 5% RH; 16L:8D h photoperiod). Results demonstrated that *C. trivialis* can successfully complete its development on all tested host plants and temperatures, except for *U. urens* at 15 and 20 °C. Mortality rates were generally higher on *U. urens*, *P. diffusa* and olive than on *S. alba*, *M. annua* and sweet orange. Both temperature and host plant significantly affected the nymphal development of *C. trivialis*. Specifically, host plant affected the development of nymphs at lower and higher temperatures (15, 20, 27 °C) but not at the optimum (24 °C) for its development temperature. Adults of *C. trivialis* lived longer on sweet orange, *M. annua* and *S. alba* in most tested temperatures compared to *U. urens*, *P. diffusa* and olives. Overall, these results suggest a better suitability of *M. annua*, *S. alba* and sweet orange compared to *U. urens*, *P. diffusa* and olive which were proven to be less suitable host plants, covering partially the nutritional needs of *C. trivialis*. The estimated lower temperature developmental threshold based on the linear model for *C. trivialis* was found to be lowest on *M. annua* (3.30 °C) and highest on *P. diffusa* (10.7 °C). The assessment of the nymphal development in various host plants and temperatures is particularly important for understanding the biology of *C. trivialis* and provides useful information to optimize its management strategy under integrated pest management system.

Keywords Mirid bug · Nymphal development · Adult longevity · Temperature threshold · Host plants

A. Kalaitzaki (✉) · I. Koufakis
Institute of Olive Tree, Subtropical Plants and Viticulture, Hellenic Agricultural Organization 'DIMITRA', Agrokipio, 731 00 Chania, Greece
e-mail: kalaitzaki@elgo.gr

A. Amara
Department of Sustainable Agriculture, Mediterranean Agronomic Institute of Chania, Alsyllion Agrokipio, P.O. Box 85, GR, 73100 Chania, Greece

S. Dervisoglou · D. Perdikis · A. Tsagkarakis
Agricultural University of Athens, Iera Odos 75, 118 55 Athens, Greece

D. Tzobanoglou
Hellenic Ministry of Rural Development and Food, Department of Rural Development of Chania, 73100, Agrokipio, Chania, Greece

Introduction

Closterotomus trivialis (Costa) (Hemiptera: Miridae) is a widely distributed phytophagous insect frequently recorded in the Mediterranean basin (Italy, Greece,

Spain, Portugal, Cyprus, Corsica, Malta) (Aukema, 2017; Barbagallo, 1970; Carapezza & Mifsud, 2015; Garcia-Marí, 2013; Yamvrias, 1998). Being a polyphagous species, its presence is common in olive and citrus orchards but also in apricot and peach as well as on a large number of weed species, the most important of which include *Mercurialis annua* L. (Euphorbiaceae), *Sinapis* sp. (Brassicaceae), *Urtica* sp. (Urticaceae), *Raphanus raphanistrum* L. (Brassicaceae), *Parietaria officinalis* L. (Urticaceae), *Sonchus oleraceu*s L. (Asteraceae), *Smyrnium olusatrum* L. (Apiaceae) and *Medicago sativa* L. (Fabaceae) (Barbagallo, 1970; Gerakaki et al., 2007; Kalaitzaki et al., 2013; Varikou & Birouraki, 2014; Yamvrias, 1998). In Italy and Greece, it completes one generation annually (univoltine). The eggs are oviposited in bark cracks and in the exposed wood of the trees at the end of spring. It overwinters at the egg stage and hatching begins in late January and then the nymph completes five instar stages to reach adulthood (Barbagallo, 1970; Yamvrias, 1998).

Early instar nymphs appear in late winter – early spring and start feeding on the young vegetation and flowers of under canopy flora while later instar nymphs and adults of the pest can move on orchard trees causing occasionally serious bud and flower abortion (Barbagallo, 1970; Kalaitzaki et al., 2013; Monaco, 1975; Varikou & Birouraki, 2014). In olive and citrus orchards of Crete (Greece), its populations start to increase from January, peaking from late January to early April while after mid-May, no individuals are recorded in the orchards (Kalaitzaki et al., 2013). Olive and citrus trees are more susceptible to *C. trivialis* damage from the early emergence of inflorescence until the initiation of blooming. The presence of eight individuals of *C. trivialis* per shoot has been reported to induce damage on the fruit setting of olive trees (Perdikis et al., 2009), while this density did not cause significant damage in citrus (Perdikis et al., 2010).

Classification of the insect is difficult in terms of pest severity since, although its population levels are usually high on weed host plants in the olive and citrus orchards, only occasional outbreaks have been reported to cause significant losses in olive and citrus production (Barbagallo, 1970; Kalaitzaki et al., 2013; Perdikis et al., 2009; Varikou & Birouraki, 2014). Likely, these outbreaks might be due to the colonization of olive and citrus trees with nymphs and adults of the pest migrating from the under canopy flora i.e. when the latter has been destroyed from herbicides or desiccation (Kalaitzaki et al., 2013; Varikou & Birouraki, 2014). Therefore, studies on host plant suitability of polyphagous insect pests which feed on both crop and non-crop host plants are essential for understanding their crop colonization rates and their damage potential and provide valuable input for the establishment of effective integrated pest management strategies (Panizzi, 1997; Panizzi & Parra, 2012).

Plant species can affect development and survival of polyphagous herbivore insects via their chemical (e.g., nutritional quality, allelochemicals) or physical (e.g., trichomes, tissue hardness) characteristics (Bernays & Chapman, 1994; Panizzi & Parra, 2012; Scriber, 1984). Plant attributes affect various biological parameters of insects: development, survival and fecundity and consequently their population density (Perdikis & Lykouressis, 2000; Rogers & Sullivan, 1986; Scriber & Slansky, 1981). In order to be qualified as a suitable host for a herbivorous insect, a specific plant species must allow insect development and successful completion at least part of its life cycle (Zalucki et al., 1986). The suitability of a particular host plant is often indicated by short developmental time and low mortality rates of an insect species (Awmack & Leather, 2002; Panizzi, 2000).

Evidence on the host plant suitability of *C. trivialis* can be inferred from previous field monitoring studies in olive and citrus groves in Crete which suggested its preference for *M. annua* followed by *R. raphanistrum*, *Urtica* sp., *P. officinalis* and *S. alba* over olive or orange trees as indicated by its population levels (Kalaitzaki et al., 2013; Varikou & Birouraki, 2014). Even though the above-mentioned studies offer valuable information, its nymphal development, mortality and adult longevity have been studied only on *R. raphanistrum* (Varikou & Birouraki, 2014). Furthermore, knowledge on the potential of each host plant species to support development and survival of the pest at different temperatures would also provide useful information for ranking the host plant suitability, especially focusing on relatively low temperatures occurring during the period of pest presence in the orchards (from January to May). Estimation of the lower temperature developmental threshold and thermal requirements of *C. trivialis* will also be useful in the prediction of population dynamics, crop colonization and the potential damage, for optimizing its management in olive or citrus orchards.

Under this light, this study aimed to: (1) study the development and survival of nymphs as well as adult longevity of *C. trivialis* when reared on 6 different host plants (*Olea europaea* L. cv. 'Koroneiki' (olive), *Citrus sinensis* L. cv. 'Washington Navel' (sweet orange), *M. annua, U. urens, P. diffusa* and *S. alba*) under four constant temperatures; (2) estimate the lower developmental temperature thresholds using a linear model; and (3) estimate the thermal requirements for development of the insect, on each host plant.

Material and methods

Instar origin, nymphal mortality and development

First instar nymphs of *C. trivialis* (as described by Hiremath & Viraktamath, 1992 for the relative species *Calocoris angustatus* Lethierry) were collected from six different host plants species (*O. europaea* cv. 'Koroneiki' (olive), *C. sinensis* cv. 'Washington Navel' (sweet orange), *M. annua*, *U. urens*, *P. diffusa* and *S. alba*) from an olive (35°29′12.8"N 24°01′28.0"E) and a citrus (35°29′31.9"N 24°03′00.1"E) orchard in the Chania prefecture (Crete, Greece), from January to April. Aerial parts of *C. trivialis* host plants were transferred from collection sites to the laboratory and inspected for the presence of first instar nymphs (eggs are not visible since they are inserted into bark cracks of trees) which were collected and transferred individually to plastic Petri dishes (Ø9 cm). Inside each Petri dish, two small stems (7–8 cm in length) with flower buds, flowers and leaves of the respective host plant were placed and the cut ends of stems were wrapped with a water-soaked cotton layer. Over 27 first-instar nymphs (replicates) were used per host plant. To ensure proper ventilation inside each Petri dish, a 3 cm-diameter hole was opened on the lid covers which was sealed with a thin muslin.

Mortality and developmental duration of *C. trivialis* nymphs were studied on stems of olive cultivar 'Koroneiki' (57th—60th phenological growth stages, according to Sanz-Corte´s et al. (2002), BBCH scale), sweet orange cv. 'Washington Navel' (59th—61st phenological growth stages according to Agusti et al. (1997), BBCH scale), *M. annua*, *U. urens*, *P. diffusa* and *S. alba* plants, that were collected from the respective olive and citrus orchards. Experiments were conducted at four constant temperatures (15, 20, 24 and 27 °C ± 0.5%), 60 ± 5% RH and 16L:8D h photoperiod and Petri dishes were randomly allocated inside growth chambers.

The mortality and developmental time of the nymphs were recorded at 12 h intervals until adult emergence. Stems in each Petri dish were replaced at a 24 h basis while the cotton was rewatered. During inspection of the Petri dishes, the presence of exuvium was used as evidence for successful molting and transition from one instar to the next. Upon adult emergence, the sex of the adults was determined. In the estimation of the nymphal development, only data from individuals that reached adulthood were used. Also, since the exact time of hatching of the first stage nymphal instars could not be determined accurately, measurements started after the molting of the nymph to the second instar (the length of the first stage nymphal instars development time is not shown in the respective tables).

Adult longevity

Randomly selected, newly emerged female and male adults (less than 24 h-old), derived from the nymphs used in the previous experiment, were used to determine the effect of host plant on *C. trivialis* longevity. The newly emerged adults were transferred in pairs in cylindrical transparent plastic cages (9 cm in diameter and 21 cm in height) and reared at the same conditions (temperature, host plant) as in the preimaginal development tests, until their death. In each cage, three small stems (7–8 cm in length) with flower buds, flowers and leaves of the tested host plant were placed in a small plastic jar (25 ml) filled with water. Stems were replaced with fresh ones every 24 h. All cages were inspected daily and mortality of the adults were recorded throughout their lifespan.

Relationship between temperature and developmental rate

Thermal requirements for the development of *C. trivialis* on each host plant were estimated using the linear model as described by Campbell et al. (1974). The temperature threshold (t) for development was estimated by extrapolating to zero the linear part of the equation representing the relationship between temperature and development

rate (the reciprocal of the average development period in days). This relationship is described by the regression equation y = a + bT where y is the rate of development, T is the temperature in °C and a and b are constants estimated with the least squares method using JMP 16.1 (SAS Institute Inc., Cary, NC, USA).

The temperature threshold was calculated as $T_{low} = -a/b$ and the thermal constant K (i.e., the amount of heat units required for development) as K = 1/b degree-days (DD) (Campbell et al., 1974). In these calculations, only the rates of development included in the linear part of development curve were used.

Statistical analysis

Percentage of nymphal mortality on different host plants within each temperature were compared using the chi square test. Furthermore, all possible pairwise comparisons between host plants within each temperature were performed using the chi square test.

The evaluation of the effects of either different temperatures or different host plants on total nymphal developmental time, developmental time of each preimaginal stage, and adult longevity was performed by ad hoc two-way analysis of variance (ANOVA). Analyses were followed by post hoc Tukey's test HSD (honestly significant differences) to compare the significance between the means ($p < 0.05$). Post hoc analysis on the effect of the sex on nymphal developmental time obtained from the study were compared using Student's t-test, at $p < 0.05$. Data analysis was carried out using the statistical program JMP 16.1 (SAS Institute, 2021).

Results

Nymphal mortality

C. trivialis could successfully complete its development on all tested host plants and temperatures, except in the case of *U. urens* at 15 and 20 °C at which no nymph survived to adulthood (Table 1). Mortality rates varied widely among different host plants within each temperature (20.5 – 100%) (Table 1). Specifically, at 15 and 20 °C, the highest mortality (100%) was observed on *U. urens* and lowest on *M. annua* and *S. alba* (15 °C: $x^2 = 45.14$, $df = 5$, $p < 0.0001$; 20 °C: $x^2 = 83.58$, $df = 5$, $p < 0.0001$). At 24 °C, the highest mortality was observed on *U. urens* and the lowest on *S. alba* and sweet orange ($x^2 = 50.81$; $df = 5$, $p < 0.0001$). No significant differences were found in mortality rates among the 6 tested host plants at 27 °C ($x^2 = 5.11$, $df = 5$, $p = 0.402$).

Nymphal development

The total period of nymphal development on each host plant at each temperature tested is shown in Table 2. Two-way ANOVA showed that both host plant ($F_{5,\ 338} = 20.05$, $p < 0.0001$) and temperature ($F_{3,\ 338} = 25.90$, $p < 0.0001$) significantly affected the nymphal development period of *C. trivialis*. Furthermore, the effect of their interaction on developmental rate was also significant ($F_{13,\ 338} = 9.92$, $p < 0.0001$) (Table 2). The shortest total developmental periods were recorded at 24 °C on *U. urens* (11.60 days), *P. diffusa* (12.05 days), *S. alba* (12.09 days) and sweet

Table 1 Percentage mortality (%) of nymphs[1] of *Closterotomus trivialis* on six host plants at various constant temperatures

Temp.°C	*Olea europaea* (n[c])	*Citrus sinensis* (n[c])	*Mercurialis annua* (n[c])	*Sinapis alba* (n[c])	*Parietaria diffusa* (n[c])	*Urtica urens* (n[c])
15	83.33 b (36)	60.00 bc (30)	39.29 ac (28)	34.37 a (32)	81.25 b (32)	100 d (28)
20	80.0 b (40)	70.00 b (40)	24.07 a (54)	36.36 a (44)	83.87 b (31)	100 c (41)
24	60.00 c (40)	33.33 ab (27)	43.33 ac (30)	20.51 b (39)	67.21 c (61)	84.62 d (65)
27	70.00 a (40)	55.00 a (40)	65.21 a (46)	51.43 a (35)	69.81 a (53)	63.64 a (33)

[1] From 2nd nymphal stage to adult emergence

[c] Initial number of replicates

Percentages followed by the same lowercase letter, within the same row, are not significantly different (chi square test, $p < 0.05$)

Table 2 Developmental time (mean ± SE) in days of *Closterotomus trivialis* nymphs[1] on six host plants at various constant temperatures

Temp.°C	*Olea europaea*	*Citrus sinensis*	*Mercurialis annua*	*Sinapis alba*	*Parietaria diffusa*	*Urtica urens*
15	30.5 ± 0.67 Ab (6)*	25.83 ± 0.53 Ac (12)	28.55 ± 0.38 Ab (17)	28.90 ± 0.43 Ab (21)	34.00 ± 0.63 Aa (6)	- (0)
20	16.87 ± 0.35 Ba (8)	17.00 ± 0.34 Ba (12)	14.90 ± 0.18 Bb (41)	14.82 ± 0.27 Bb (28)	17.60 ± 0.87 Ba (5)	- (0)
24	12.37 ± 0.49 Ca (16)	12.33 ± 0.11 Ca (18)	12.94 ± 0.36 Ca (17)	12.09 ± 0.19 Ca (31)	12.05 ± 0.58 Ca (20)	11.60 ± 0.45 Aa (10)
27	12.33 ± 0.14 Cb (12)	12.89 ± 0.33 Cb (18)	12.75 ± 0.88 Cb (16)	13.35 ± 0.45 Db (17)	16.12 ± 0.66 Ba (16)	13.41 ± 0.76 Ab (12)

[1] From 2nd nymphal stage to adult emergence

* Number of individuals that completed development

Means followed by different capital letters within the same column are significantly different ($p < 0.05$; HSD test)

Means followed by different small letters within the same row are significantly different ($p < 0.05$; HSD test)

orange (2.33 days) while on olive (12.33 days) and *M. annua* (12.75 days) the respective shortest development periods were recorded at 27 °C. However, significant differences for nymphal development of *C. trivialis* between tested host plants were not found at 24 and 27 °C, except on *P. diffusa* at 27 °C in which development was significantly longer. The longest total developmental periods were recorded on *P. diffusa* (34 days) and olive (30.5 days) at 15 °C. Concerning *U. urens,* no nymph completed its development at 15 and 20 °C (Table 2 and 3).

The developmental period of the various nymphal stages on the six tested host plants at 15–27 °C is shown in Table 3. Host plant significantly affected the length of development of each nymphal instar at all temperatures examined, except 24 °C.

Sex did not significantly affect the length of development periods in any of the temperature/host plant combinations tested ($t = 1.41$, $p = 0.16$).

Adult longevity

The two—way ANOVA showed that both temperature ($F_{3,277} = 28.86$, $p < 0.0001$) and host plant ($F_{5,277} = 16.67$, $p < 0.0001$) significantly affected adult longevity of *C. trivialis*. Furthermore, the effect of their interaction on adult longevity was also significant ($F_{13,277} = 3.21$, $p = 0.0002$) (Table 4). Adults' longevity was significantly longer when they were reared on *S. alba*, *M. annua* and sweet orange compared to *P. diffusa* at 15 °C, and on sweet orange at 20 °C, compared to *P. diffusa* and olives. At 24 °C, *C. trivialis* lived significantly longer on *S. alba* and sweet orange compared *P. diffusa* and *U. urens.* At 27 °C, no significant differences were found on adulthood longevity of *C. trivialis* between the tested host plants.

Relationship between temperature and developmental rate

The linear model fitted well the data on developmental rate on all tested host plants (excluding *U. urens*) (Table 5). The estimated temperature threshold for the nymphal development of *C. trivialis* was found to be lowest on *M. annua* and highest on *P. diffusa*. Specifically, the temperature thresholds for development were estimated to be 3.30 °C on *M. annua,* 5.97 °C on olive, 7 °C on sweet orange, 8.13 °C on *S. alba* and 10.7 oC on *P. diffusa* (Table 5). Lowest numbers of degree-days were found on *P. diffusa* and highest on *M. annua*. In particular, the degree-days for the completion of nymphal development were 271, 238, 212, 189 and 153 DD on *M. annua*, olive, sweet orange, *S. alba* and *P. diffusa*, respectively (Table 5).

Discussion

Results showed that both cultivated (olive and citrus) and weed (*M. annua, S. alba, U. urens, P. diffusa*) plant species tested are suitable hosts for nymphal

Table 3 Developmental time (mean ± SE) in days of the nymphal stages[1] of *Closterotomus trivialis* on six host plants at various constant temperatures

Temp. °C	Host plant	2nd instar	3rd instar	4th instar	5th instar
15	*Olea europaea*	6.33 ± 0.21a	7.16 ± 0.31 b	7.17 ± 0.40 ab	9.83 ± 0.16 abc
	Citrus sinensis	4.50 ± 0.15 bc	6.33 ± 0.22 bc	6.66 ± 0.33 bc	8.33 ± 0.51 c
	Mercurialis annua	6.11 ± 0.19 a	5.78 ± 0.12 bcd	6.11 ± 0.16 bc	10.55 ± 0.16 ab
	Sinapis alba	5.81 ± 0.27 a	5.62 ± 0.14 bcd	6.47 ± 0.21 bc	11.00 ± 0.34 a
	Parietaria diffusa	6.00 ± 0.36 a	10.66 ± 0.21 a	7.00 ± 0.36 a	10.33 ± 0.42 bc
	Urtica urens	5.64 ± 0.37 ab	6.62 ± 0.82 bc	5.00 ± 0.57 cd	-
20	*Olea europaea*	3.25 ± 0.16 def	3.75 ± 0.25 efg	4.50 ± 0.46 d	5.37 ± 0.26 defg
	Citrus sinensis	3.50 ± 0.23cde	3.50 ± 0.15 fg	4.00 ± 0.17 de	6.00 ± 0.46 d
	Mercurialis annua	3.29 ± 0.12 de	3.22 ± 0.10 fg	3.56 ± 0.07 def	4.83 ± 0.11 defgh
	Sinapis alba	2.82 ± 0.13 efg	2.82 ± 0.16 fg	3.53 ± 0.15 def	5.64 ± 0.11de
	Parietaria diffusa	3.60 ± 0.24 cde	3.80 ± 0.37 defg	4.00 ± 0.44 de	6.00 ± 0.02 d
	Urtica urens	4.25 ± 0.31 cd	4.75 ± 0.47 cdef	-	-
24	*Olea europaea*	2.50 ± 0.13 efg	3.00 ± 0.26 fg	2.87 ± 0.21 ef	4.00 ± 0.13 ghi
	Citrus sinensis	2.33 ± 0.11 fg	3.16 ± 0.16 fg	3.00 ± 0.19 ef	3.83 ± 0.09 hi
	Mercurialis annua	2.29 ± 0.21 fg	2.65 ± 0.20 fg	3.29 ± 0.25 def	4.71 ± 0.21 efghi
	Sinapis alba	2.22 ± 0.07 fg	2.83 ± 0.16 fg	2.87 ± 0.07 f	4.16 ± 0.08 ghi
	Parietaria diffusa	2.30 ± 0.29 fg	2.60 ± 0.25 f	2.85 ± 0.25 f	4.30 ± 0.34 fghi
	Urtica urens	1.80 ± 0.13 g	2.50 ± 0.37 g	2.80 ± 0.25 f	4.50 ± 0.37 efghi
27	*Olea europaea*	3.00 ± 0.17 defg	2.83 ± 0.11 fg	2.83 ± 0.11 f	3.66 ± 0.14 i
	Citrus sinensis	2.89 ± 0.14efg	3.22 ± 0.19 fg	3.00 ± 0.23 ef	3.78 ± 0.15 i
	Mercurialis annua	2.25 ± 0.18 fg	2.63 ± 0.26 g	2.88 ± 0.22 ef	5.00 ± 0.38 defgh
	Sinapis alba	2.37 ± 0.12 fg	2.41 ± 0.17 g	3.52 ± 0.21 def	5.05 ± 0.22defg
	Parietaria diffusa	2.25 ± 0.25 fg	5.00 ± 0.59 cde	4.25 ± 0.11 d	4.62 ± 0.29 efghi
	Urtica urens	2.33 ± 0.28 fg	3.16 ± 0.60 fg	3.41 ± 0.35 def	4.50 ± 0.19 efghi

-, No nymph completed development

[1] From 2nd nymphal stage to adult emergence

Means followed by different lowercase letters within the same column are significantly different ($p < 0.05$; HSD test)

Table 4 Adult longevity (mean ± SE) in days of *Closterotomus trivialis* on six host plants at various constant temperatures

Temp.°C	*Olea europaea*	*Citrus sinensis*	*Mercurialis annua*	*Sinapis alba*	*Parietaria diffusa*	*Urtica urens*
15	33.50 ± 2.32 Aa (12)*	33.50 ± 2.12 Aa (12)	39.28 ± 2.15 Aa (14)	39.76 ± 2.32 Aa (13)	19.00 ± 3.79 Ab (16)	-
20	6.00 ± 1.77 Bb (16)	14.25 ± 1.76 Ba (16)	9.66 ± 1.81 Bab (15)	8.99 ± 1.88 Bab (14)	4.90 ± 2.12 Bb (11)	-
24	6.75 ± 2.12 Bbc (16)	14.83 ± 2.01 Bab (18)	7.66 ± 2.45 BCab (12)	16.75 ± 2.12 Ba (16)	3.08 ± 2.45 Bc (12)	1.30 ± 0.19 Ac (10)
27	2.12 ± 0.87 Bb (16)	3.35 ± 0.94 Cab (14)	4.07 ± 0.94 Cab (14)	6.60 ± 1.11 Ba (10)	4.27 ± 1.06 Bab (11)	1.27 ± 0.69 Ab (11)

* Number of individuals that completed development

Means followed by different capital letters within the same column are significantly different ($p < 0.05$; HSD test)

Means followed by different small letters within the same row are significantly different ($p < 0.05$; HSD test)

Table 5 Thermal requirements and lower thermal threshold temperatures for development of *C. trivialis* reared on five different host plants

Host plant	df	[1]Regression equation	S.E. of *b*	R^2	[2]T_{LOW}	[3] *K*
Olea europaea	42	y = -0.0251 + 0.0042 T	0.00040	0.731*	5.97	238
Citrus sinensis	41	y = -0.0329 + 0.0047 T	0.00015	0.961*	7.00	212
Mercurialis annua	91	y = -0.01219 + 0.0037 T	0.00025	0.708*	3.30	271
Sinapis alba	80	y = -0.0431 + 0.0053 T	0.00021	0.892*	8.13	189
Parietaria diffusa	30	y = -0.0696 + 0.0065 T	0.00095	0.617*	10.68	153

* $p < 0.05$

[1]Equation of the linear temperature dependent model of developmental rate (y = a + bT, where y is the rate of development, T is the temperature in °C and a and b are estimated constants)

[2]T_{LOW}: lower developmental threshold temperature (°C)

[3] *K*: Thermal constant (degree-days)

development of *C. trivialis* at almost all temperatures tested, except on *U. urens* at 15 and 20 °C. Mortality rates were generally higher on *U. urens*, *P. diffusa* and olive, followed by sweet orange, *M. annua* and *S. alba*. At most temperatures developmental rate was favored on *M. annua* and *S. alba*. Generally, *C. trivialis* developed faster and in similar rates at 24 and 27 °C (except on *P. diffusa* at 27 °C) and was significantly reduced at 15 °C. Mortality rates were minimum on *S. alba* (20.5%) and *M. annua* (24.1%) at 24 and 20 °C, respectively and maximum on *U. urens* (100%) at 15 and 20 °C. An earlier laboratory study on another host weed species, *R. raphanistrum,* showed a faster nymphal development of *C. trivialis* at higher temperatures, ranging from 30 to 32.5 °C, with the minimum mortality recorded at 20 °C (10.34%) and the maximum at 35 °C (100%) (Varikou & Birouraki, 2014). Therefore, *R. raphanistrum* should also be considered a suitable host plant for nymphal development and survival of *C. trivialis*.

Interestingly, and in contrast to the results of a previous study reporting that *Urtica* sp. was the second most preferable host of the insect nymphs from end of February to early April (Kalaitzaki et al., 2013), our results showed that *U. urens* did not support the completion of *C. trivialis* nymphal development at 15 and 20 °C. In addition, *C. trivialis* had a prolonged nymphal development period on *P. diffusa* at 15 and 27 °C. Likely, *C. trivialis* development is obstructed on species belonging to the Urticaceae family at these temperatures. A possible explanation could be the lower suitability of plant sap for nymphal development in plant tissues (e.g., low levels of nitrogen) (Awmack & Leather, 2002; Panizzi, 2000). In addition, species of the Urticaceae family produce secondary metabolites that either kill or retard the development of insects (War et al., 2012). It is possible that these weed species serve as hosts for the pest only for a short period, probably covering part of its nutritional needs or providing shelter against natural enemies (Panizzi, 2000).

Our study found that both temperature and host plant significantly influenced the nymphal development of *C. trivialis*. Plant host species affected the development of nymphs at lower and higher temperatures but not at the optimum for its development temperature. This interacting effect of diet quality with temperature on the insect performance has been observed in other cases in the literature. For example, differences on the length of the developmental period of the mirid *Macrolophus pygmaeus* (Rambur) (Hemiptera: Miridae) were observed only at low and high temperatures between two eggplant cultivars (Lykouressis et al., 2001). Additionally, Combs and Valerio (1980) have observed differences on the development period of *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) on different varieties of *Cynodon dactylon* L. (Poaceae) at 20 and 25 °C, but not at 30 °C which was proven to be a favorable temperature. According to Quispe-Tarqui et al. (2021) the interaction between temperature and diet observed in the development rate of *Copitarsia incommoda* Walker (Lepidoptera: Noctuidae) can be attributed to the effect of temperature on food intake rate. In the study of Larsen et al. (1990) johnsongrass appeared to be more suitable than oats or maize for

the development of *Graminella nigrifrons* (Forbes) (Hemiptera: Cicadellidae) at 18 °C, but the reverse was true at 30 °C.

Although the growing period of all tested weed host plants coincides with the occurrence of the *C. trivialis* (winter until late spring) in the field (Kalaitzaki et al., 2013), the estimated temperature threshold based on thermal requirements for the nymphal development of *C. trivialis* differed greatly in different host plants. Specifically, it was found to be lowest on *M. annua* (3.30 °C) and highest on *P. diffusa* (10.7 °C). The temperature thresholds for the nymphal development on *M. annua*, olive, sweet orange, and *S. alba,* were below the winter mean minimum temperature of Chania during the coldest months (January-March) which is approximately 9 °C (1955- 2018). Similarly, a threshold of 7 °C was estimated for *C. trivialis* on *R. raphanistrum* by Varikou and Birouraki (2014).

The degree-days needed for the completion of nymphal development were estimated to be highest on *M. annua* (271 DD) and lowest on *P. diffusa* (153 DD) while the respective DD value recorded by Varikou and Birouraki (2014) on *R. raphanistrum* was 212.7 DD.

Host plant species and temperature had a significant effect on adulthood longevity. Adult longevity was higher at 15 °C on all tested host plants and was reduced dramatically at higher temperatures. Similarly, adult longevity was highest at 15 °C (45.28 days) on *R. raphanistrum* and remained high up to 25 °C, while significant reduction was observed at 30 and 32.5 °C (Varikou & Birouraki, 2014). Adults of *C. trivialis* lived longer when they were reared on sweet orange, *M. annua* and *S. alba* in most tested temperatures compared to the other weed species or olive trees, suggesting a good suitability of these plant species as hosts for adults. However, field observations showed that only *M. annua* support significantly higher adult populations (Kalaitzaki et al., 2013). In *U. urens,* the longevity of adults was very low even in higher temperatures in which nymphal development was completed successfully. This result is in accordance with previous studies reporting relatively low abundance of adults on *Urtica* sp. on both olive and citrus orchards in Crete (Kalaitzaki et al., 2013), suggesting that this weed species is not a suitable host for adult feeding. Also, when reared on olive, adults lived less compared to alternative weed hosts such as *M. annua* or *S. alba*, in most temperatures.

M. annua was found to be the most suitable host plant for *C. trivialis* based on the low temperature threshold, short nymphal developmental period, low nymphal mortality and relatively high adult longevity especially at low temperatures typically observed in the field during the period of pest appearance which is 15 days earlier than in the other host plants (Kalaitzaki et al., 2013).

On olive, nymphal survival and adult longevity of *C. trivialis* was low, clearly indicating that this economically important crop is a less suitable host serving as an occasional source of nutrients and an overwintering site. This is in agreement with field observations reporting extremely low *C. trivialis* populations from late January to late spring, and limited injury levels caused by the insect on olives early in the growing season and only in cases where the surrounding weed hosts had been destroyed by herbicide applications or had begun to desiccate (Kalaitzaki et al., 2013; Perdikis et al., 2009; Varikou & Birouraki, 2014).

In case of citrus, the low preference of *C. trivialis* nymphs for this host over most of the weeds tested under field conditions (Kalaitzaki et al., 2013; Varikou & Birouraki, 2014) cannot sufficiently be justified in association with the tested biological parameters (shortest nymphal development period at 15 °C, low mortality at 24 °C and high adult longevity at 20 and 24 °C). This might be due to the non-synchronization of the appearance of the nymphs with the appropriate phenological stage of the sweet orange suitable for their feeding. In natural settings, under typical Mediterranean weather conditions, there is only a small time-window where the appropriate phenological stage of sweet orange (flower buds and flowers) (from March to mid-May) for the nutrition of nymphs coincides with the population peak of *C. trivialis* nymphs (late January to early April) forcing them to feed on different flowering plant species.

In any case, the relationship between host preference of weed species, present in a crop orchard and the injury levels inflicted to the cultivated plants is complex. Presence of suitable weed hosts in the appropriate growth stage seems to mitigate the loss of flower buds and blossom of olive and citrus since the insect prefers weeds over the crop trees. Furthermore, observations in olive orchards with the non-host plant *Oxalis* sp. demonstrated extremely low or even the absence of the *C. trivialis* population both in weed and olive tree canopy (Kalaitzaki unpublished data). In the latter case, insecticide applications are unnecessary and should be avoided.

Concluding, the most suitable tested weeds are *M. annua* and *S. alba* and thus higher numbers of the pest are expected in orchards with these weeds, directly affecting the survivorship and population growth of *C. trivialis* within an olive and citrus ecosystem. Sweet orange was also found to be a suitable host, however the non-synchronization of the peak performance of *C. trivialis* nymphs in the field with the appropriate phenological host stage, probably forces them to feed on different flowering plant species. *Urtica urens*, *P. diffusa* and olive were proven to be less suitable host plants, covering partially the nutritional needs for the development of the nymphs.

Overall, results from this study on comparative suitability between weeds and crops are particularly important for understanding the biology of *C. trivialis* and support the development of ecologically based pest management tactics against this pest. In this respect, host-weed diversity in olive or citrus orchards should be maintained, during the critical period of flower buds emergence until beginning of blooming of crops, while the presence of less or non-host weeds should be taken into account in order to avoid unnecessary insecticide treatments. Further laboratory experiments should focus on the chemical (e.g. nutritional quality, allelochemicals) and/or physical (e.g., trichomes, tissue hardness) characteristics that are responsible for host preference.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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References

Agusti, M., Zaragoza, S., Bleiholder, H., Buhr, L., Hack, H., Klose, R., & Stauss, R. (1997). Adaptation of the BBCH scale for the description of citrus fruits phenological stages. *Fruits, 52*(5), 287–295.

Aukema, B. (2017). *Closterotomus trivialis* (A. Costa, 1853). Fauna Europaea version 2017.06. https://fauna-eu.org. Accessed 11 Oct 2021

Awmack, C. S., & Leather, S. R. (2002). Host plant quality and fecundity in herbivorous insects. *Annual Review of Entomology, 47*, 817–844.

Barbagallo, S. (1970). Contributo alla conoscenza del *Calocoris* (*Closterotomus*) *trivialis* (Costa) (Rhynchota-Heteroptera, Miridae). *Entomologica, 6*, 1–104.

Bernays, E. A., & Chapman, R. F. (1994). *Host-plant selection by phytophagous insects*. Springer Science & Business Media.

Campbell, A., Frazer, B., Gilbert, N., Gutierrez, A., & Mackauer, M. (1974). Temperature requirements of some aphids and their parasites. *Journal of Applied Ecology, 11*, 431–438.

Carapezza, A., & Mifsud, D. (2015). New records of true bugs (Hemiptera, Heteroptera) from the Maltese Islands. *Bulletin of the Entomological Society of Malta, 7*, 27–50.

Combs, R. L., & Valerio, J. R. (1980). Biology of fall armyworn on four varieties of bermudagrass when held at constant temperatures. *Environmental Entomology, 9*, 393–396.

Garcia-Marí, F. (2013). Patterns of change in population abundance of citrus pest species obtained from an area-wide field survey and monitoring network established in eastern Spain. *IOBC-WPRS Bulletin, 95*, 55–60.

Gerakaki, K. P., Kalaitzaki, A. P., Varikou, K. N., & Alexandrakis, V. Z. (2007). *Calocoris trivialis* Costa (Hemiptera: Miridae) a pest of olive orchards of country of Chania. Proceedings of the 12th National Entomological Meeting of Entomological Society of Greece (Larnaca, Cyprus), pp. 64–66.

Hiremath, I. G., & Viraktamath, C. A. (1992). Biology of the sorghum earhead bug, *Calocoris angustatus* (Hemiptera: Miridae) with description of various stages. *International Journal of Tropical Insect Science, 13*(3), 447–457.

Kalaitzaki, A., Amara, A., & Tsagkarakis, A. (2013). Seasonal phenology and relative preference of *Closterotomus trivialis* on olive, citrus and weeds in the field. *Applied Entomology and Zoology, 48*, 57–63.

Larsen, K. J., Madden, L. V., & Nault, L. R. (1990). Effect of temperature and host plant on the development of the blackfaced leafhopper. *Entomologia Experimentalis et Applicata, 55*, 285–294.

Lykouressis, D. P., Perdikis, DCh., & Michalaki, M. P. (2001). Nymphal development and survival of *Macrolophus pygmaeus* Rambur (Hemiptera: Miridae) on two eggplant

varieties as affected by temperature and presence/absence of prey. *Biological Control, 20*, 222–227.

Monaco, R. (1975). Preoccupante ricomparsa di *Calocoris trivialis* Costa sull'olivo in Puglia. *Informatore Fitopatologico, 25*(9), 5–7.

Panizzi, A. R. (1997). Wild hosts of pentatomids: Ecological significance and role in their pest status on crops. *Annual Review of Entomology, 42*, 99–122.

Panizzi, A. R. (2000). Suboptimal nutrition and feeding behavior of hemipterans on less preferred plant food sources. *Anais Da Sociedade Entomológica do Brasil, 29*, 1–12.

Panizzi, A. R., & Parra, J. R. (2012). *Insect bioecology and nutrition for integrated pest management*. CRC Press.

Perdikis, D., Garantonakis, N., Kitsis, P., Giatropoulos, A., Paraskevopoulos, A., Cassis, G., & Panagakis, S. (2009). Studies on the damage potential of *Closterotomus trivialis* and *Aphanosoma italicum* on olive fruit setting. *Bulletin of Insectology, 62*(2), 215–219.

Perdikis, D., & Lykouressis, D. (2000). Effects of Various Items, Host Plants, and Temperatures on the Development and Survival of *Macrolophus pygmaeus* Rambur (Hemiptera: Miridae). *Biological Control, 17*, 55–60.

Perdikis, D., Panagakis, S., & Maselou, D. (2010). Studies on the damage potential of *Closterotomus* (= *Calocoris*) *trivialis* and *Aphanosoma italicum* (Hemiptera: Miridae) on citrus. *Journal of Pest Science, 83*(2), 113–119.

Quispe-Tarqui, R., Yujra Pari, J., Callizaya Condori, F., & Rebaudo, F. (2021). The effect of diet interacting with temperature on the development rate of a Noctuidae quinoa pest. *Environmental Entomology, 50*(3), 685–691.

Rogers, D. J., & Sullivan, M. J. (1986). Nymphal performance of *Geocoris punctipes* (Hemiptera: Lygaeidae) on pest-resistant soybeans. *Environmental Entomology, 15*, 1032–1036.

Sanz-Corte´s, F., Martinez-Calvo, J., Badenes, M. L., Bleiholder, H., Hack, H., Llacer, G., & Meier, U. (2002). Phenological growth stages of olive trees (Olea europaea). *Annals of Applied Biology, 140*, 151–157.

SAS Institute. (2021). *JMP version 16.1*. SAS Institute Inc., Cary, USA.

Scriber, J. M. (1984). Host-plant suitability. In W. J. Bell & R. T. Carde (Eds.), *Chemical Ecology of Insects* (pp. 159–202). Springer.

Scriber, J. M., & Slansky, F. (1981). The nutritional ecology of immature insects. *Annual Review of Entomology, 26*, 183–211.

Varikou, K., & Birouraki, A. (2014). Life history of *Closterotomus* (*Calocoris*) *trivialis* (Costa) (Heteroptera: Miridae) in olive and citrus orchards in Crete. *Crop Protection, 59*, 14–21.

War, A. R., Paulraj, M. G., Ahmad, T., Buhroo, A. A., Hussain, B., Ignacimuthu, S., & Sharma, H. C. (2012). Mechanisms of plant defense against insect herbivores. *Plant Signaling & Behavior, 7*(10), 1306–1320.

Yamvrias, C. (1998). *Agricultural entomology, entomological pests of olive trees*. Stamoulis Publishers.

Zalucki, M. P., Daglish, G., Firempong, S., & Twine, P. H. (1986). The biology and ecology of *Heliothis armigera* (Hübner) and *H. punctigera* Wallengren (Lepidoptera: Noctuidae) in Australia: What do we know? *Australian Journal of Zoology, 34*, 779–814.

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