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Demographic characteristics and population projection of *Phytonemus pallidus fragariae* reared on different strawberry cultivars

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Abstract
The strawberry mite, *Phytonemus pallidus fragariae* (Banks) (Acari: Tarsonemidae), is one of the most important pests of greenhouse grown strawberry plants. Field grown strawberries may also be infested by the pest in high humid conditions. Life tables give the most comprehensive description of the development, survival, stage differentiation, reproduction and consequently population growth of a population, and thus it is an important base of population ecology and pest management. In this study, to provide a comprehensive evaluation of an ecology-based and cost-effective control program, life history and demographic parameters of the strawberry mite were studied. The experiment was conducted under laboratory conditions providing 20 ± 1 °C, 80 ± 10% RH and L16:D8 photoperiod. The data were analyzed based on the age-stage, two-sex life table theory. The population parameters net reproduction rate ($R_0 = 6.14$ offspring), intrinsic rate of increase ($r = 0.1317$ day^{-1}), and finite rate of increase ($\lambda = 1.1407$ day^{-1}) on cv. Aromas were lower than those on the other cultivars tested. Based on the population characteristics, Aromas is a less favorable cultivar for the population growth of strawberry mite.

Keywords Strawberry mite · Host plant resistance · Age-stage two-sex life table

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Introduction

Strawberries are important crops for many small-scale and part-time farming operations in many countries including Iran (Mass 1987; Lopez-Aranda et al. 2011; Azadi Dana et al. 2018b). Because of the crop's high value and demand, strawberry pests such as tarnished plant bug, *Lygus lineolaris* (Parisolt de Beauvois) (Hemiptera: Miridae), strawberry bud weevil, *Anthonomus signatus* (Say) (Coleoptera: Curculionidae), and strawberry mite or strawberry tarsonemid mite, *Phytonemus* (*Steneotarsonemus*) *pallidus fragariae* (Banks) (Acari: Tarsonemidae), are intensively managed. Tolerance to pests on crops eaten unprocessed is low and potential exposure to pesticide residue is high (Handley and Dill 2009). *Phytonemus pallidus fragariae* is an important pest of strawberry in many countries in Europe and North America (Labanowska 2004) and also in Iran. Feeding by this mite weakens the plant and can cause reductions in yield when its population density is high (Alford 1972; Stenseth and Nordby 1976). Problems with this pest are becoming increasingly serious as more strawberry crops are grown in polyethylene tunnels and glasshouses (Easterbrook et al. 2001).

Chemical control of strawberry mite is difficult, due to the limited number of approved pesticides. Additionally, there is strong pressure to reduce pesticide use. Host plant resistance is one of the alternative methods that affect plant development, pest population density and damage and the number of pesticide applications (Zehnder et al. 2007). Use of resistant or less favorable crop cultivars is considered one of the major components of an ecological and economic pest control program (Özgökçe and Atlihan 2005). Therefore, to select resistant or non-preferred cultivars of the same plant at the beginning of production is important. The fitness of a pest population represents its damage capacity to a host plant, and it can properly be ascertained through the use of life tables, because life tables can provide an integrated and comprehensive description of the development, survival, and reproduction of a population. Life table is a useful tool for predicting the population growth potential of an insect pest under a given selection of hosts (Soleimannejad et al. 2010; Karimi et al. 2012; Khanamani et al. 2013; Safuraie-Parizi et al. 2014; Efe et al. 2015; Özgökçe et al. 2018a, b; Nikooei et al. 2015), and its parameters are used to evaluate the level of a plant's resistance to pests and to design a comprehensive IPM program.

In this study, three cultivars of strawberry (Paros, Kurdistani and Aromas) were selected for a life table study of strawberry mite. The main purpose of the current study is to examine how different cultivars of strawberry affect the population growth of the strawberry mite. The data can be used in an area-wide management of strawberry mite, where various strawberries are cultivated.

Materials and methods

Strawberry mite rearing

Strawberry plants of cvs. Paros, Kurdistani and Aromas, were planted in pots containing approximately 30 kg of mixture of soil, sand and peat (1:1:1), and were infested with strawberry mite. The mites used in the experiments were originally collected from strawberry fields having cultivars tested (Paros, Kurdistani and Aromas) in Sanandaj, Iran, in 2016. Stock cultures were reared in a greenhouse at 25 ± 1 °C, 80 ± 10% RH and L14:D10 h photoperiod.

Life table studies

The mite was reared on leaves of the respective host plants for two generations before use in experiments to eliminate effects of previous hosts. The experiments were initiated with 50 eggs laid within 24 h. Eggs were maintained separately in individual cages. Modified Munger cells (Druciarek et al. 2014) were used in this study. Observations were made at 24-h intervals with a stereomicroscope. The development of strawberry mites from egg to adult was determined on strawberry cultivars under laboratory conditions at 20 ± 1 °C, 80 ± 10% RH and L16:D8 photoperiod.

After emergence of adults, females and males were paired, and survival and fecundity data were recorded daily until the death of each individual. Dead males were replaced with live males during the observation period. Thus, males and females were kept together up to the end of the study.

Data analysis

The life history raw data of all individuals were analyzed based on the age-stage, two-sex life table theory (Chi and Liu 1985; Chi 1988). The life table parameters were calculated accordingly, including age-stage specific survival rate (s_{xj}) (where x = age in days and j = stage), age-stage-specific fecundity (f_x) (daily number of eggs produced per female of age x), age-specific survival rate (l_x), age specific fecundity (m_x), and the population growth parameters net reproductive rate (R_0), intrinsic rate of increase (r), finite rate of increase (λ), and mean generation time (T). Age-specific survival rate (l_x), and age-specific fecundity (m_x) for individuals aged x are calculated as:

$$l_x = \sum_{j=1}^{k} s_{xj}, \tag{1}$$

$$m_x = \frac{\sum_{j=1}^{k} s_{xj} f_{xj}}{\sum_{j=1}^{k} s_{xj}}, \tag{2}$$

where k is the number of stages.

The net reproduction rate is defined as the mean number of offspring that an individual can produce during its lifetime and is calculated as:

$$R_0 = \sum_{x=0}^{\infty} l_x m_x. \tag{3}$$

The intrinsic rate of increase was estimated from the Euler–Lotka formula using the method of iterative bisection with the age indexed from 0 (Goodman 1982) as:

$$\sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1. \tag{4}$$

The finite rate (λ) is calculated as:

$$\lambda = e^r. \tag{5}$$

The mean generation time is the period that a population needs to increase to R_0-fold of its size as the population reaches the stable age-stage distribution and is calculated as:

$$T = \frac{\ln R_0}{r}. \tag{6}$$

The life expectancy (e_{xj}) is the period that an individual of age x and stage j is expected to live and it is calculated according to Chi and Su (2006) as:

$$e_{xj} = \sum_{i=x}^{\infty} \sum_{y=j}^{k} s'_{iy}, \tag{7}$$

where s'_{iy} is the probability that individuals of age x and stage j will survive to age i and stage y and, is calculated by assuming $s'_{xj} = 1$. The reproductive value (v_{xj}) was calculated according to Tuan et al. (2014a, b) as:

$$v_{xj} = \frac{e^{r(x+1)}}{s_{xj}} \sum_{i=x}^{\infty} e^{-r(i+1)} \sum_{y=j}^{k} s'_{iy} f_{iy}. \tag{8}$$

The standard errors of the developmental times, survival, fecundity, longevity and population parameters were estimated by using the bootstrap method with 100,000 × resampling (Efron and Tibshirani 1993; Polat-Akköprü et al. 2015). The paired bootstrap test was used to compare differences (Efron and Tibshirani 1993). The computer program TWOSEX-MSChart (Chi 2017a) was used for the raw data analysis and calculation of population parameters, and routines for both the bootstrap and paired bootstrap test were included in this program.

Population projection

To project the population growth, we used the method of Chi (1990) and the computer program TIMING (Chi 2017b). The population growth of the pest was simulated on the three strawberry cultivars for 30 days using an initial population of 10 newly laid eggs. To show the variability of population growth, we sorted the 100,000 bootstrap results of the finite rate (λ) to find the 2.5th and 97.5th percentiles, i.e., the 2500th and 97,500th sorted bootstrap samples. We then used the bootstrap life table samples that generated the 2.5th and 97.5th percentiles of λ to project the population growth. The results represent the confidence interval of the population growth.

Results

There were no significant differences in egg incubation period on the three strawberry varieties, and larval stage duration was the longest on cv. Kurdistani (Table 1). Feeding on the various strawberry cultivars did not change the preadult development time of the cohort or of females, but it did changed male preadult duration; the shortest time was obtained on cv. Paros. Preadult mortality was highest on cv. Aromas (Table 1). Feeding on the different strawberry cultivars affected the probability that a newly laid strawberry mite egg will survive to the adult stage. The highest age-stage specific survival rate, s_{xj}, was obtained on

Table 1 Mean (±SE; *n* in parentheses) developmental time (days) and mortality rate of *Phytonemus pallidus fragariae* reared on the three strawberry cultivars Kurdistani, Aromas and Paros

Parameter	Kurdistani	Aromas	Paros
Egg	4.0±0.1a (50)	4.2±0.1a (50)	4.1±0.1a (50)
Larva	3.7±0.1a (47)	3.5±0.1ab (43)	3.4±0.1b (45)
Female preadult	7.8±0.1aA (31)	7.8±0.1aA (25)	7.8±0.1aA (28)
Male preadult	8.0±0.2aA (16)	7.8±0.2bA (18)	7.3±0.2bB (17)
Cohort preadult	7.85±0.101a (47)	7.79±0.108a (43)	7.62±0.111a (45)
Preadult mortality rate	0.06±0.034a (47)	0.14±0.049a (43)	0.10±0.043a (45)

Standard errors were estimated by using the bootstrap technique with 100,000 resampling. Means followed by the same lower case letter indicate no significant difference between varieties, whereas means followed by the same capital letter indicate no significant difference between sexes (paired bootstrap test: $P > 0.05$)

cv. Kurdistani (0.94), followed by cvs. Paros (0.90) and Aromas (0.86) (Fig. 1). The s_{xj} also displays stage differentiation among individuals of the pest; due to the variable developmental rate among individuals, significant overlap can be observed (Fig. 1). Duration of the adult longevity of females varied among strawberry cultivars and the longest period was observed on cv. Kurdistani. No significant differences were found in male adult longevity among the cultivars. The highest values of total longevity of females and males were obtained on Kurdistani. Adult duration and total longevity of females was longer than those of males on every strawberry cv. tested (Table 2). There were no significant differences in adult and total pre-oviposition period among the three cvs. The highest mean fecundity and the longest oviposition period of strawberry mite were obtained on cv. Kurdistani. The post-oviposition period was the longest on cv. Aromas (Table 2).

On all three varieties, oviposition of strawberry mite began at age 8 days. The highest age-specific fecundity ($m_x = 1.6$ eggs) was observed on cv. Kurdistani at age 16 days (Fig. 2) whereas the highest net maternity ($l_x m_x = 1.1$ offspring) value was on Paros at age 12 days (Fig. 2).

The curves of life expectancy (e_{xj})—the time that individuals of age x and stage j are expected to live after age x—in general, decreased with age, because no other mortality factors existed under the laboratory conditions except aging (Fig. 3). The age-stage reproductive value (v_{xj})—indicating the contribution of an individual at age x and stage j to the future population—increased significantly when adults emerged and the peak of v_{xj} of the pest appeared at age 10 days on all cvs (Fig. 4), very close to the total pre-oviposition period values.

There were no significant differences in the intrinsic rate of increase (r), finite rate of increase (λ), net reproductive rate (R_0) and mean generation time (T) of the pest among the strawberry cultivars tested (Table 3). Although there were no significant differences among strawberry cultivars for population parameters (r, λ, R_0), the projected total population size of the pest on cv. Kurdistani (514.13 individuals) was considerably higher than that on Aromas (286.80) and Paros (383.99) (Fig. 5). The variability of the projected population growth obtained by using the 2.5th and 97.5th percentiles revealed that feeding on different strawberry cultivars did not affect the variability of the population growth, and there was a high degree of uncertainty in the population growth of the pest on all three cultivars (Fig. 5).

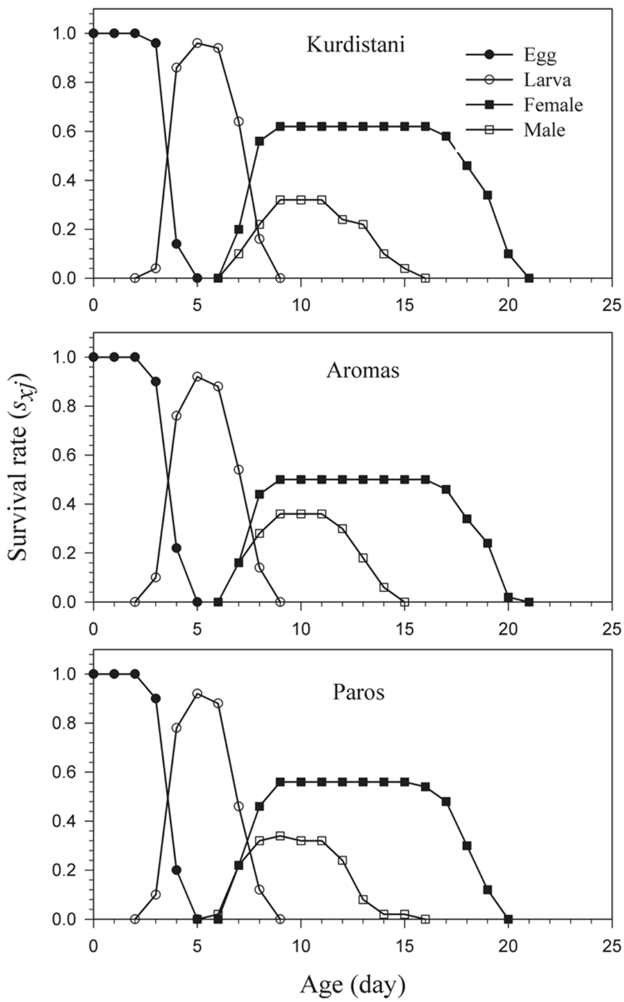

Fig. 1 Age-stage specific survival rate (s_{xj}) of *Phytonemus pallidus fragariae* reared on three strawberry cultivars

Discussion

Despite the strawberry mite being a widely distributed pest of field and greenhouse strawberries (Zalom et al. 2006), few demographic studies as regards its various host plants have been published (Easterbrook et al. 2003; Labanowska 2004); hence, the present findings can form a useful addition. In this study, the egg incubation period of the strawberry mite on the three strawberry cultivars varied from 4.0 to 4.2 days which was shorter than the period reported by Easterbrook et al. (2003). This discrepancy may be attributed to differences in temperature and nutritional quality of strawberry cultivars used. Although fecundity obtained in this study was much lower than fecundity obtained by Azadi Dana et al. (2018a) for two-spotted spider mite (*Tetranychus urticae* Koch) on Kurdistani, Aromas and

Table 2 Mean (±SE; *n* in parentheses) adult pre-oviposition, oviposition and total pre-oviposition period, oviposition period, post-oviposition period, fecundity, and longevity of *Phytonemus pallidus fragariae* reared on the three strawberry cultivars Kurdistani, Aromas and Paros

Parameter	Kurdistani	Aromas	Paros
Adult pre-oviposition period (days)	1.5 ± 0.12a (31)	1.7 ± 0.11a (25)	1.7 ± 0.09a (28)
Total pre-oviposition period (days)	9.3 ± 0.15a (31)	9.5 ± 0.2a (25)	9.5 ± 0.16a (28)
Oviposition period (days)	8.9 ± 0.17a (31)	8.2 ± 0.09b (25)	8.2 ± 0.12b (28)
Post-oviposition period (days)	1.6 ± 0.17b (31)	2.1 ± 0.21a (25)	1.5 ± 0.13b (28)
Fecundity (no. eggs/female)	13.7 ± 0.21a (31)	12.3 ± 0.12b (25)	12.5 ± 0.17b (28)
Female adult longevity (days)	11.6 ± 0.2aA (31)	11.3 ± 0.2aA (25)	10.8 ± 0.2bA (28)
Male adult longevity (days)	5.8 ± 0.2aB (16)	5.7 ± 0.2aB (18)	5.6 ± 0.2aB (17)
Female total longevity (days)	19.4 ± 0.2aA (31)	19.1 ± 0.2abA (25)	18.6 ± 0.2bA (28)
Male total longevity (days)	13.9 ± 0.3aB (16)	13.5 ± 0.2abB (18)	12.9 ± 0.3bB (17)

Standard errors were estimated by using the bootstrap technique with 100,000 resampling. Means followed by the same lower case letter indicate no significant difference between varieties, whereas means followed by the same capital letter indicate no significant difference between sexes (paired bootstrap test: $P > 0.05$)

Paros cvs., the values of intrinsic rate of increase, an important indicator of population growth, were higher for strawberry mite due to considerably lower developmental time. In the present study, the strawberry mite reared on Aromas laid 12.3 eggs at 20 °C which is less than that reported by Monteiro et al. (2014) for two-spotted spider mite on Aromas (25.1 eggs at 25 °C).

Feeding on different strawberry cultivars affected survival rate, fecundity and adult female longevity of the pest—all three were the highest on cv. Kurdistani. Differences in these biological characteristics did not change population parameters (R_0, r, λ, and T). As the intrinsic rate of increase (r) and finite rate of increase (λ) reflect combined effects of biological characteristics viz., survival, development, and reproduction, these parameters best describe and evaluate the growth a population of arthropods under certain environmental conditions—r and λ are key demographic parameters used to estimate an arthropod's ability to develop and a host plant to be resistant (Razdoburdin 2006; Negloh et al. 2008; Safuraie-Parizi et al. 2014). The estimated r and λ values in the current study varied from 0.1317 to 0.1539 day^{-1}, and 1.1407 to 1.1664 day^{-1}, respectively. Although there were no significant differences in r and λ of the strawberry mite reared on the strawberry cultivars, the values were lowest on cv. Aromas, and the projected population growth on this cultivar was 25.3 and 44.2% lower than on Paros and Kurdistani, respectively. Similar to our results, in several studies it is shown that even a small reduction in the intrinsic rate of increase can ultimately cause considerable change in a pest's population size (Goundoudaki et al. 2003; Özgökçe and Atlihan 2005; Efe and Özgökçe 2014; Tuan et al. 2016; Chang et al. 2016; Bussaman et al. 2017; Atlihan et al. 2017).

The main commercial cultivar grown in Iran, especially in the north-west (Kurdistan), is cv. Kurdistani. The cultivars Aromas and Paros have been grown in the center of Iran. All of these cultivars have been found to be attacked by the strawberry mite in commercial fields. In general, all commercial strawberry cvs. are host of the strawberry mite, but some are much more susceptible to mite attack than others (Zalom et al. 2006). Population projections in the current study indicated that cv. Aromas is the less susceptible among the cultivars tested. Differences in population growth of the strawberry mite among strawberry cultivars may be due to differences in plant physical texture—e.g., cuticle thickness

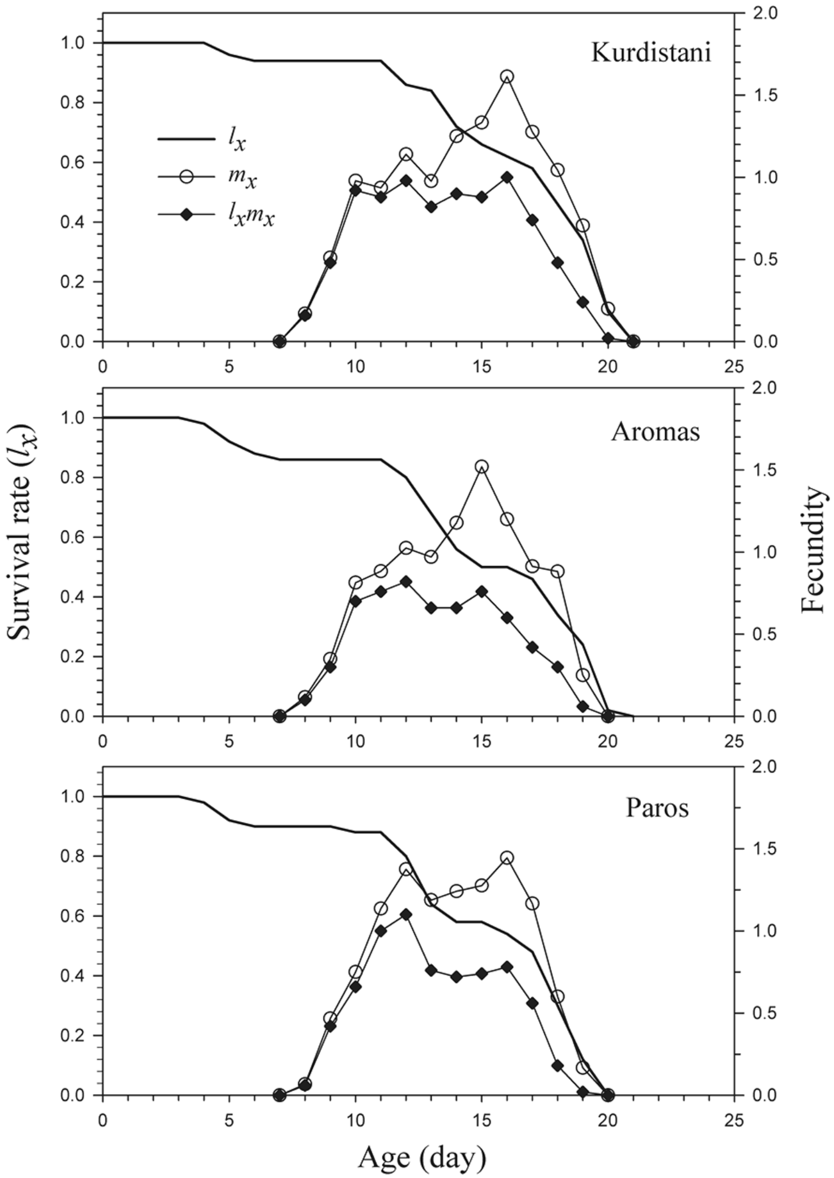

Fig. 2 Age specific survival rate (l_x), fecundity (m_x), and net maternity (l_xm_x) of *Phytonemus pallidus fragariae* reared on three strawberry cultivars

and presence of glandular or non-glandular hairs—, nutritional value, and physiology. It is known that such plant characteristics affect population growth performance of mites (Kerguelen and Hoddle 2000; van den Boom et al. 2003; Kasap 2003, 2004; Kafil et al. 2007; Vásquez et al. 2008; Amil-Ruiz et al. 2011; Monteiro et al. 2014; Azadi Dana et al. 2018a, b).

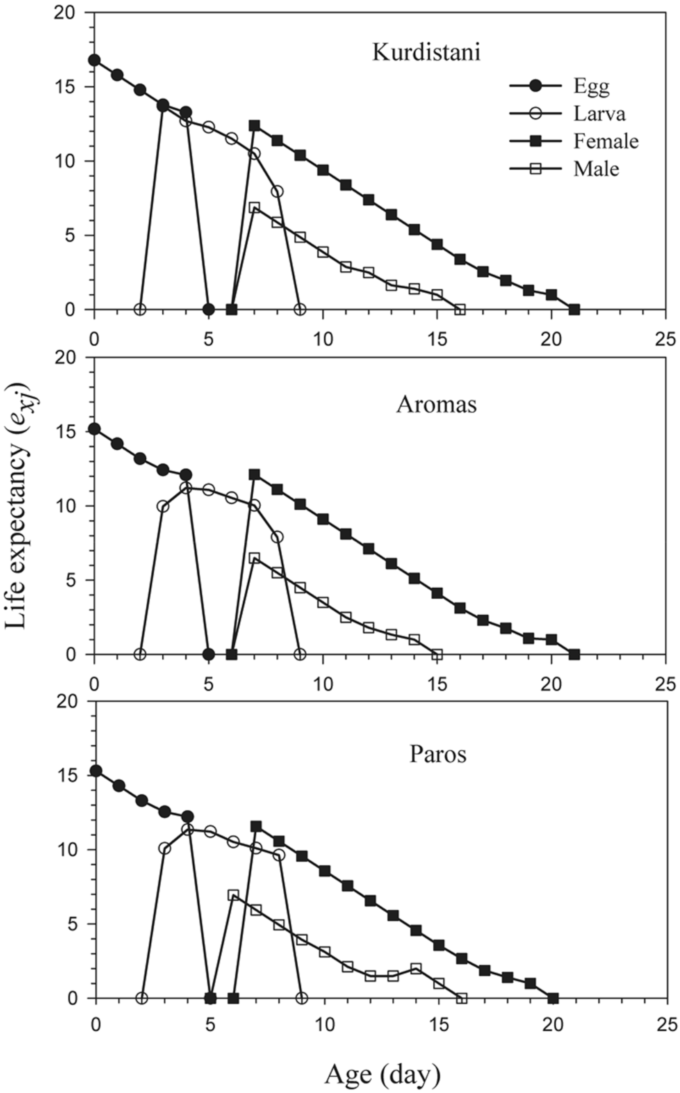

Fig. 3 Age-stage specific life expectancy (e_{xj}) of *Phytonemus pallidus fragariae* reared on three strawberry cultivars

The projected population growth on cv. Aromas indicated a slower increase in the pest population, which offers a higher chance for effective biological control and other management strategies. The lower population growth on Aromas may reduce the application of insecticides, and may also reduce the need for persistent pesticides with the associated risk of contaminating food and the environment. Because life table data—developmental time, survival and fecundity—are collected from a population of limited size, the variability or

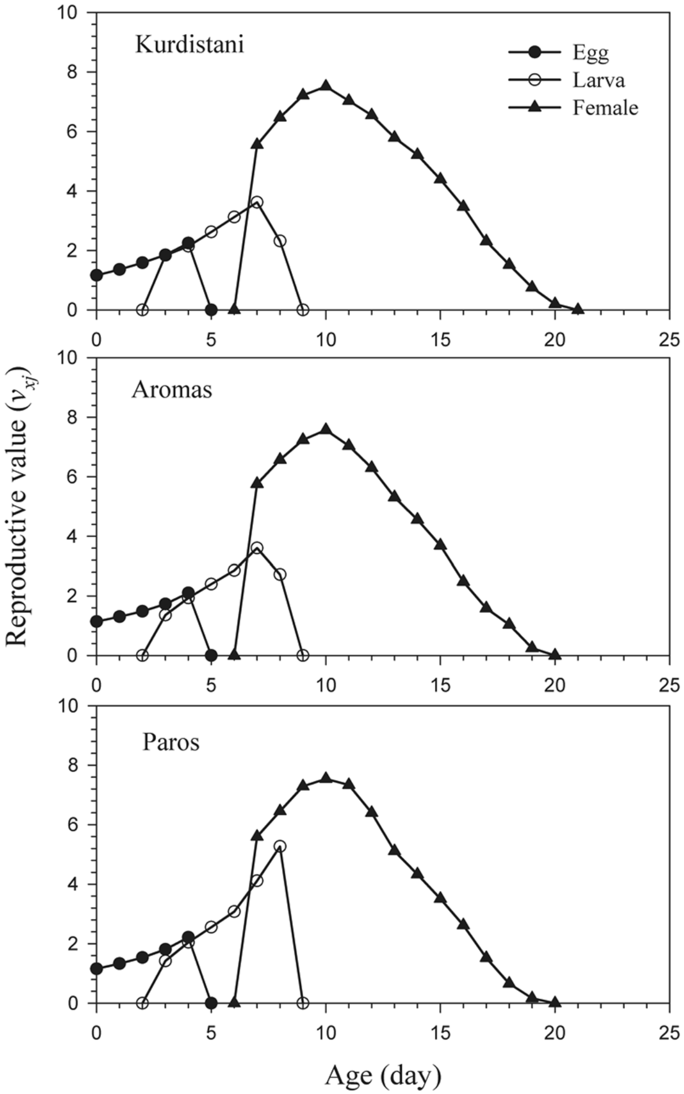

Fig. 4 Age-stage specific reproductive value (v_{xj}) of *Phytonemus pallidus fragariae* reared on three strawberry cultivars

Table 3 Mean (± SE) life table parameters of *Phytonemus pallidus fragariae* reared on the three strawberry cultivars Kurdistani, Aromas and Paros

Parameter	Kurdistani	Aromas	Paros
Net reproductive rate, R_0 (no. offspring/individual)	8.50 ± 0.94	6.14 ± 0.87	7.00 ± 0.87
Intrinsic rate of increase, r (day^{-1})	0.1539 ± 0.0087	0.1317 ± 0.0111	0.1424 ± 0.0098
Finite rate of increase, λ (day^{-1})	1.1664 ± 0.0101	1.1407 ± 0.0126	1.1530 ± 0.0113
Mean generation time, T (days)	13.90 ± 0.17	13.77 ± 0.20	13.67 ± 0.15

Standard errors were estimated by using the bootstrap technique with 100,000 resampling. Means did not differ significantly between varieties (paired bootstrap test: $P > 0.05$)

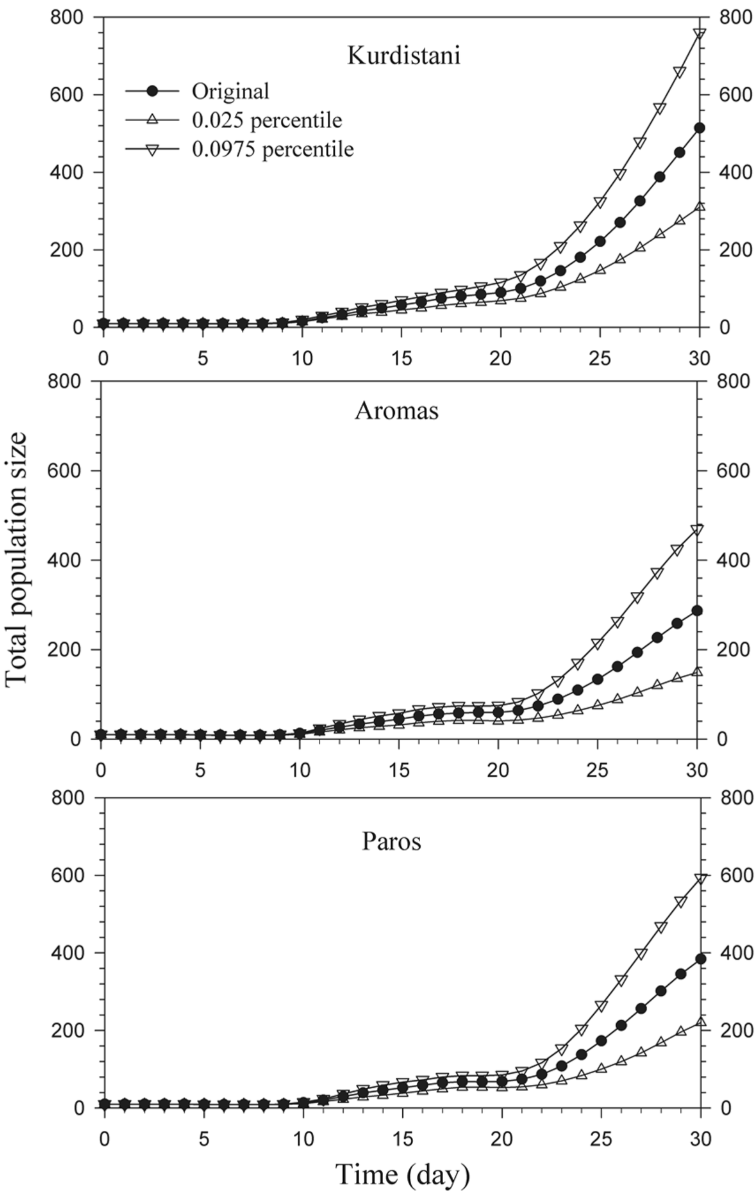

Fig. 5 Projection of population growth of *Phytonemus pallidus fragariae* reared on three strawberry cultivars and the uncertainty based on the 2.5th and 97.5th percentiles of confidence interval of the finite rate of increase

uncertainty of population growth should be projected for the practical application of life tables to ecological research and pest management (Huang and Chi 2012; Huang et al. 2018). In this study, a high degree of variability in the population growth of the pest was obtained on all three strawberry cultivars. Still, our findings can be considered by growers in order to construct an IPM program for the control of strawberry mite.

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