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Influence of climate factors on population density and damage of the leopard moth, *Zeuzera pyrina* L., in walnut orchards, Iran

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Abstract

The effect of climate factors (temperature, humidity, precipitation, and frost days) on the population changes, damage, and infestation area of the leopard moth, *Zeuzera pyrina* L., was studied during 2006–2018 in four parts of Iran including Saman, Arak, Najaf-abad, and Baft. For trend analysis, the Mann–Kendall test was run on time series data of both climate and pest population. According to the results, the annual mean (Kendall's statistics, $T = 0.64$ and 0.48), annual minimum ($T = 0.60$ and 0.42), and January mean ($T = 0.64$ and 0.61, respectively) temperatures showed increasing trends in Saman and Najaf-abad. Moreover, the annual mean minimum and January temperatures ($T = 0.41$ and 0.45, respectively) in Arak and the annual mean maximum temperature ($T = 0.79$) in Baft showed increasing trends. The number of frost days/year (Kendall's statistics, $T = -0.63$, -0.53, -0.32 and -0.37) and annual mean relative humidity ($T = -0.43$, -0.63, -0.64 and -0.42, respectively) showed decreasing trends in Saman, Arak, Baft, and Najaf-abad stations. Trend analysis indicated significant increases in the mean number of moths caught ($T = 0.59$, 0.76 and 0.90), the percentage of infested branches/tree ($T = 0.66$, 0.58, and 0.90), the number of active holes/tree ($T = 0.79$, 0.55, and 0.68) and the infested areas ($T = 0.99$, 0.73, and 0.98, respectively) in Saman, Arak and Najaf-abad stations. According to stepwise regression, the mean temperatures of January, autumn, and winter were the most effective variables for increasing *Z. pyrina* damage and population, while relative humidity and the number of frost days played the major role in reducing it.

Introduction

The leopard moth, *Zeuzera pyrina* L. (Lepidoptera: Cossidae), is a dangerous wood-boring insect that is considered the most important pest of the walnut (Kutinkova *et al.*, 2006; Saeidi et al., 2022), olive (Hegazi *et al.*, 2009), and apple (Almanoufi *et al.*, 2012) in Iran and other countries. The pest larvae cause serious damage to the trees by boring into the twigs, branches, and trunks, weakening and sometimes killing them (Kutinkova *et al.*, 2006; Hegazi *et al.*, 2015; Saeidi, 2020). Like other insects, the pest is a poikilothermic organism and the temperature of its body depends on the environmental temperature. According to Kocmánková *et al.* (2010), temperature is probably the most important environmental factor affecting the population dynamics of insects. Temperature, precipitation, and humidity are the most important factors which affect the distribution and seasonal activity of insect pests under field conditions (Ullah *et al.*, 2012; Bayu *et al.*, 2017; Islam *et al.*, 2017; Shimazaki *et al.*, 2019). Moreover, many researchers reported that the population growth parameters of insects and mites such as developmental rate, survival, reproduction, and longevity vary with the climate factors (El-Halawany and Abdel-wahed, 2013; Riahi *et al.*, 2013).

Changes in temperature and other climate factors influence directly and indirectly agricultural crops and their corresponding pests (Skendžic *et al.*, 2021). Climate factors directly impact the pests' life-table parameters, whereas they indirectly affect the relationships between pests, their host plants, environment, and other insect species (Prakash *et al.*, 2014). According to Liang and Elbakidze (2011), there is a significant relationship between changes in environmental factors and pests outbreak. Various studies investigated the impact of climate changes on the distributions, migration, population changes, and damage of insect pests such as the onion thrips, *Thrips tabaci* Lindeman (Bergant *et al.*, 2005), Lepidoptera species (Sparks *et al.*, 2007), the plain tiger, *Anosia chrysippus* L. (Sudan *et al.*, 2015), the peach twig borer, *Anarsia lineatella* Zeller (Saeidi, 2019) and the leopard moth, *Z. pyrina* (Fekrat and Farashi, 2022).

Considering the importance of the climate variables, this research was undertaken to investigate the effect of climate factors on the population changes, damage and infestation area of the leopard moth in four different parts of Iran, including Chaharmahal va Bakhtiari, Kerman, Isfahan, and Markazi provinces which severely infested by *Z. pyrina*. The results may be useful to predict the pest population status in the future under climate change scenarios and to develop a successful integrated *Z. pyrina* management programme.

Materials and methods

Meteorological data

The climate factors studied were: average of annual mean temperature, annual mean minimum temperature, annual mean maximum temperature, annual absolute minimum temperature, annual absolute maximum temperature, mean temperature of January, February, July and August, mean temperature of autumn, winter, spring and summer, the number of frost days per year, annual relative humidity, and annual precipitation. Meteorological data of four synoptic stations in different provinces including Saman (Chaharmahal va Bakhtiari province), Najaf-Abad (Isfahan), Arak (Markazi), and Baft (Kerman) were obtained from Iran Meteorological Organization. The geographical coordinates of the studied orchards and their distance from the nearest station are given in table 1.

Seasonal activity of the pest

Seasonal flight of the adults was studied during 2006–2018 using sex pheromone traps. Two walnut orchards in each region, with 3–5 km distances apart, were selected. Walnut trees were approximately 15–20 years old, 13–14 m high, and planted at $10 \times 8\ \text{m}^2$ distances between and along the rows. No chemical was applied on experimental plots during the period of study. The pheromone dispensers, type of trap, and installation height were followed according to Saeidi (2020). Four sex pheromone-baited traps were installed in each orchard and to avoid interference between them, the distance between two adjacent traps was 50 m (Ardeh *et al.*, 2014). All traps were set at a height of 1 m below the apical point of the trees' canopy and leaves and branches were removed around their entrances (Saeidi *et al.*, 2022). The traps were set-up in each location from 10 May (before the emergence of adult males) to 15 July (the end of the adults' flight) to monitor the pest population. Pheromone traps were checked twice a week until the capture of first adult and then once a week to record the number of captured moths. The sticky sheets and the pheromone lures were replaced every 2 weeks and every month, respectively.

Twig infestation

Since the young larvae bore into twigs, the number of infested twigs/tree was determined in each orchard during the second week of August, when the activity of larvae was maximal on the twigs. For this purpose, 20 trees in each location were selected randomly and ten random twigs (60 cm length), from each side of the tree at mid height, were examined and the infestation ratio was calculated.

Number of active galleries/tree

The number of active galleries/tree was determined during the second week of October, when the 4th and 5th instar larvae bore into trunk and main branches. For this purpose, 20 trees in each orchard were selected randomly and the number of active galleries on the trunk (up to 4 m height) was recorded.

The infested areas

The areas infested (ha) by *Z. pyrina* in the studied provinces (including Chaharmahal va Bakhtiari, Isfahan, Markazi, and Kerman) were obtained from Plant Protection Organization, Ministry of Agriculture, Iran.

Trend analysis

The widely used Mann–Kendall test was run at 95% confidence level on time series data of both climate and pest population for the time period 2006–2018. According to this test, the null hypothesis, H0 assumes that there is no trend (the data are independent and randomly ordered) and this is tested against the alternative hypothesis H1, which assumes that there is a trend. If the P value is less than the significance level α (alpha = 0.05), H0 is rejected. Rejecting H0 indicates that there is a trend, while accepting H0 indicates no trend in the time series (Kendall, 1975; Pohlert, 2016).

Software used for performing the statistical Mann–Kendall test was Addinsoft's XLSTAT 2018. In addition, to compare the results obtained from the Mann–Kendall test, linear trend lines are plotted using Microsoft Excel 2007. Pearson's correlation coefficient was used to determine the effect of climate factors on population changes and damage caused by the pest on walnut trees. Moreover, stepwise regression was used to find a set of climate variables that significantly influence the population and damage of *Z. pyrina*.

Results

Comparison of climate factors

Saman synoptic station: the average of annual mean temperature from 2006 to 2018 at Saman synoptic station was 13.63 ± 0.72°C (±SE), ranging from 11.75 to 14.94°C. Therefore the annual average temperature in the hottest year (2016) increased by 3.24°C compared to the coldest year (2013) (table 2). The same trend was observed in different months, especially in winter. January and February showed the highest increase (12.50 and 7.93°C, respectively) in temperature in the hottest year compared to the coldest one (table 2). The annual mean maximum temperature from 2006 to 2018 was 20.55 ± 0.28°C, ranging from 18.23 to 22.26°C (4.03°C difference), whereas the annual mean minimum temperature was 6.24 ± 0.34°C with a range of 2.95–7.63°C (table 2). The highest number of frost days was recorded during the 2006–2007 growing season (122 days) and the lowest during 2017–2018 (6 days). The lowest annual absolute minimum temperature (−21.8°C) corresponds to 2007–2008 and the highest (−6.8°C) to the growing period 2016–2017 (table 2). The annual rainfall ranged from 155.7 mm (in 2017–2018) to 511.40 mm (in 2007–2008), with a mean of 298.70 ± 26.42 mm. The mean annual relative humidity was 34.73 ± 0.73% with a range of 30.95–37.80% (table 2).

Arak synoptic station: the annual mean temperature, annual mean maximum temperature, and annual mean minimum temperature from 2006 to 2018 were 14.80 ± 0.51, 20.83 ± 0.55, and

Table 1. Geographical coordinates of the studied orchards and their nearest synoptic stations

Synoptic stations	Geographical coordinates (latitude and longitude)	Station altitude (m)	Orchard name	Geographical coordinates	Distance from the station (km)
Saman (Bakhtiari province)	32.43 N, 50.87 E	1936	Lagdom	32.44 N, 50. 89 E	2
			Hossain-abad	32.47 N, 50.90 E	5
Arak (Markazi province)	34.06 N, 49.42 E	1703	Arak 1	34.08 N, 49.22 E	2.30
			Arak 2	33.54 N, 49.29 E	2.70
Baft (Kerman province)	29.14 N, 56.35 E	2280	Bagher-abad	29.23 N, 56.56 E	3
			Garigan	29.22 N, 56.59 E	4
Najaf-abad (Isfahan province)	32.38 N, 51.22 E	1641	Najaf-abad 1	32.36 N, 51.26 E	4.5
			Najaf-abad 2	32.19 N, 51.22 E	5

8.39 ± 0.49°C, respectively. The highest and the lowest number of frost days were 105 and 31, respectively. The lowest annual absolute minimum temperature (−12.8°C) corresponds to 2007–2008 and the highest (−6.8°C) to the growing period 2016–2017 (table 2). The mean annual rainfall during this period was 298.70 ± 26.42 mm, ranging from 166.80 mm (in 2016–17) to 499.70 mm (in 2014–15). The mean annual relative humidity was 43.50 ± 0.76% with a range of 39.80–78.80% (table 2).

Baft synoptic station: the annual mean temperature, annual mean maximum temperature, and annual mean minimum temperature were 15.24 ± 0.18, 23.32 ± 0.70, and 7.45 ± 0.74°C, respectively (table 2). The highest increase in annual mean, maximum, and minimum temperatures were observed in the winter season (January and February). The highest number of frost days was recorded during 2006–2007 (81 days), whereas the lowest was related to 2016–2017 (37 days). The lowest annual absolute minimum temperature (−12.00°C) was observed in 2007–2008 and the highest (−6.00°C) in the growing period 2017–2018 (table 2). The mean annual rainfall was 251.90 ± 23.64 mm, with a range of 134.3 mm (in 2007–2008) to 467.20 mm (in 2017–2018). The mean annual relative humidity was 35.71 ± 1.11% with a range of 31.60–45.40% (table 2).

Najaf-abad synoptic station: the annual mean temperature, annual mean maximum temperature, and annual mean minimum temperature were 16.70 ± 0.20, 24.10 ± 0.20, and 9.50 ± 0.20°C, respectively (table 2). Similar to the other stations, the largest increase in mean, maximum, and minimum annual temperatures occurred in winter. The number of frost days ranged from 89 days (in 2006–2007) to 13 days (in 2017–2018). The lowest annual absolute minimum temperature (−12.20°C) corresponds to 2007–2008 and the highest (−5.00) to the growing season 2016–2017 (table 2). The annual rainfall was 120.90 ± 14.60 mm ranging from 47.90 mm (in 2007–2008) to 193.70 mm (in 2012–13). The mean annual relative humidity was 34.40 ± 1.00% with a range of 30.70–42.10% (table 2).

Changes in the population of the leopard moth

Saman (Chaharmahal va Bakhtiari): the average number of moths caught (in each trap), the percentage of infested branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) during the studied period (2006–2018) were 49.83 ± 4.84 (±SE), 57.91 ± 4.02, 37.83 ± 4.97, and 566.6 ± 89.53, respectively. The highest number of moths caught (per trap) was observed in the growing season 2017–2018, whereas the lowest occurred in 2006–2007 and 2012–2013. A similar trend was observed in the percentage of infested branches and the number of active holes/tree. The infested areas by the pest increased from 100 ha (in 2006–2007) to 1100 ha in 2017–2018 growing season (table 3).

Baft (Kerman province): the average number of moths caught (in each trap), the percentage of infested branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) during the studied years (2006–2018) were 39.41 ± 3.30, 45.41 ± 3.83, 3.13 ± 0.26, and 256.60 ± 26.02, respectively. The highest number of moths caught (in each trap) was observed in growing season 2010–2011 and the lowest in 2006–2007. The highest percentage of infested branches and the number of active holes/tree were observed in 2007–2008 and 2009–2010, respectively. Similar to the Saman station, the infested walnut orchards increased from 75 ha (in 2006–2007) to 360 ha in 2017–2018 growing season (table 3).

Arak (Markazi province): the average number of moths caught (in each trap), the percentage of infested branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) during the studied years (2006–2018) were 90.67 ± 5.88, 24.33 ± 2.35, 3.92 ± 0.89, and 670.80 ± 57.72, respectively. The highest number of moths caught (in each trap) was observed in growing season 2017–2018 and the lowest in 2007–2008. The highest percentage of infested branches and the number of active holes/tree were observed in 2017–2018. The infested areas increased from 350 ha (in 2006–2007) to 900 ha in 2017–2018 growing season (table 3).

Najaf-abad (Isfahan province): the average number of moths caught (in each trap), the percentage of infected branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) during the studied years (2006–2018) were 54.30 ± 4.80, 52.90 ± 4.20, 6.70 ± 0.40, and 495.00 ± 52.30, respectively. The highest number of moths caught (in each trap) was observed in the growing season 2017–2018 and the lowest in 2006–2007. Moreover, the highest percentage of infested branches and the number of active galleries/tree were observed in 2017–2018. As in the other regions, the area of infested walnut orchards increased from 270 ha (in 2006–2007) to 800 ha in 2017–2018 (table 3).

Trends in the climate variables

Saman: in the studied period (2006–2018), the mean temperature of the annual, winter, and autumn seasons showed increasing

Table 2. Mean of different climate variables in the studied synoptic stations from 2007 to 2018

Synoptic stations	Saman			Arak			Baft			Najaf-abad		
Climate variables	Mean	SE	Range	Mean	SE	Range	Mean	SE	Range	Mean	SE	Range
No. of frost days	30.16	8.77	6–122	48.6	6.18	31–105	52.58	3.73	37-81	67.1	3.6	50 -89
Annual absolute minimum temperature	−12.69	1.63	−21.8 to −7	−3.25	1.02	−12.8 to 1.2	−8.76	0.71	−12 to −4.6	−8	0.8	−12.2 to −3.8
Annual absolute maximum temperature	36.68	0.24	35.6–38.5	35.78	0.23	34.5–37.3	35.75	0.18	34.6–36.8	40.3	0.2	39.2–41.6
Annual mean maximum temperature	20.55	0.28	18.23–22.26	20.83	0.55	15.9–24.2	23.32	0.7	19.9–26.7	24.1	0.2	22.6–25.6
Annual mean minimum temperature	6.24	0.34	2.95–7.63	8.39	0.49	4.7–11.3	7.45	0.74	3.5–10.1	9.5	0.2	8.4–10.3
Annual mean temperature	13.36	0.27	11.69–14.94	14.8	0.51	10.8–18.5	15.24	0.18	13.7–16.1	16.7	0.2	15.5–17.7
Annual precipitation	298.7	26.42	155.7–511.4	281	26.55	166.8–499.7	251.9	23.64	134.3–467.2	120.9	14.6	47.9–197.3
Annual relative humidity	34.73	0.73	30.95– 38.73	43.5	0.76	39.8–48.8	35.71	1.11	31.6–45.4	34.4	1	30.7–42.1
January mean temperature	1.05	1.09	−5.8 to 5.7	1.72	1.2	−8.3 to 6.4	4.84	0.47	1.4–6.9	3.8	0.7	−0.8 to 6.6
February mean temperature	2.42	0.67	−0.8 to 7.1	2.77	1.13	−7.1 to 7.5	5.51	0.4	3.7–7.6	5.9	0.5	3.3–9.10
July mean temperature	24.98	0.28	22.4–26.1	27.05	0.31	24.4–28.4	25.48	0.63	24.3–27.4	29.2	0.2	28.1–30.2
August mean temperature	24.09	0.52	19.5–26.3	27.71	0.19	26.3–28.6	24.95	0.3	22.9–26.9	28.2	0.4	26.5–30.3
Autumn mean temperature	10.35	0.27	8.6–11.8	10.85	0.28	9.4–12.4	12.02	0.25	10.7–13.6	12.9	0.2	11.7–14.1
Winter mean temperature	3.44	0.6	−0.6 to 6.7	3.5	0.8	−2.5 to 6.6	6.55	0.3	5.07–8.47	6.5	0.5	4.5–8.9
Spring mean temperature	16.02	0.28	14.2–17.6	17.33	0.25	15.8–18.7	18.11	0.49	13.03– 20.07	19.9	0.2	18.4–20.9
Summer mean temperature	23.59	0.35	20.2–24.9	26.19	0.13	25.4–27.2	24.27	0.23	22.37– 25.07	27.6	0.2	26.5–29.4

Table 3. Mean number of moths caught (in each trap), the percentage of infected branches/tree (in August), the number of active holes/tree (in November), and the infested areas (ha) in different locations during the studied period 2006–2018

	Saman				Arak				Baft				Najaf-abad			
Year	No. of moths	Infected branches (%)	No. of holes	Infected areas (ha)	No. of moths	Infected branches (%)	No. of holes	Infected areas (ha)	No. of moths	Infected branches (%)	No. of holes	Infected areas (ha)	No. of moths	Infected branches (%)	No. of holes	Infected areas (ha)
2006–2007	29	31	16	100	82	35	4	350	17	67	4.2	70	35	30	5	270
2007–2008	23	43	22	150	46	16	1	350	27	73	3.8	110	38	35	5	270
2008–2009	26	50	28	250	55	15	2	430	24			230	43	38	6	300
2009–2010	45	53	30	350	83	23	2	540	42	53	4.9	230	43	40	5	300
2010–2011	63	67	35	400	96	22	1	680	59	47	3.1	230	40	50	7	420
2011–2012	60	69	38	550	97	25	3	700	54	41	3.7	230	45	55	7	450
2012–2013	28	72	21	600	98	22	2	850	47	35	2.7	270	60	62	8	520
2013–2014	41	43	32	700	95	31	4	800	39	33		310	45	50	7	560
2014–2015	51	51	42	800	109	24	2	950	37	37	2.1	340	65	60	6	640
2015–2016	60	68	48	850	108	25	6	800	37	41	2.4	350	74	65	7	680
2016–2017	68	73	68	950	103	12	9	700	43	27	1.9	350	79	70	8	730
2017–2018	84	75	74	1100	116	42	11	900	45	38	2.3	360	85	80	9	800
Mean	49.83	57.91	37.83	566.6	90.67	24.33	3.92	670.83	39.41	45.41	3.13	256.6	54.3	52.9	6.7	495
SE	4.84	4.02	4.97	89.53	5.88	2.35	0.89	57.72	3.3	3.83	0.26	26.02	4.8	4.2	0.4	52.3

Table 4. Mann–Kendall trend analysis of time series data of climate variables for the time period 2006–2018

	Saman			Arak			Baft			Najaf-abad		
	Kendall's statistics (*T*)	*P*-value	Trend	Kendall's statistics (*T*)	*P*-value	Trend	Kendall's statistics (*T*)	*P*-value	Trend	Kendall's statistics (*T*)	*P*-value	Trend
No. of frost days	−0.63	0.006	Decreasing	−0.53	0.05	Decreasing	−0.32	0.17	Decreasing	−0.37	0.11	Decreasing
Annual absolute minimum temperature	0.48	0.03	Increasing	0.15	0.53	No trend	0.20	0.40	No trend	0.36	0.12	No trend
Annual absolute maximum temperature	0.24	0.31	No trend	−0.15	0.54	No trend	−0.34	0.14	No trend	−0.09	0.73	No trend
Annual mean maximum temperature	0.606	0.005	Increasing	0.11	0.68	No trend	0.79	0.001	Increasing	0.03	0.94	No trend
Annual mean minimum temperature	0.61	0.005	Increasing	0.41	0.07	Increasing	−0.67	0.002	Decreasing	0.48	0.03	Increasing
Annual mean temperature	0.64	0.003	Increasing	0.28	0.24	No trend	−0.21	0.38	No trend	0.42	0.06	Increasing
January mean temperature	0.64	0.003	Increasing	0.45	0.04	Increasing	0.32	0.17	No trend	0.61	0.009	Increasing
February mean temperature	0.42	0.06	Increasing	0.35	0.13	No trend	0.26	0.27	No trend	0.26	0.27	No trend
July mean temperature	0.055	0.88	No trend	0.27	0.24	No trend	−0.19	0.41	No trend	−0.03	0.94	No trend
August mean temperature	0.18	0.48	No trend	0.078	0.78	No trend	−0.11	0.68	No trend	0.27	0.24	No trend
Autumn mean temperature	0.59	0.009	Increasing	−0.11	0.68	No trend	−0.36	0.11	No trend	0.29	0.21	No trend
Winter mean temperature	0.53	0.01	Increasing	0.21	0.37	No trend	0.19	0.41	No trend	0.33	0.15	No trend
Spring mean temperature	0.25	0.30	No trend	0.24	0.31	No trend	0.015	0.30	No trend	0.21	0.37	No trend
Summer mean temperature	0.34	0.15	No trend	0.092	0.73	No trend	−0.13	0.58	No trend	0.21	0.37	No trend
Annual precipitation	−0.12	0.64	No trend	−0.18	0.45	No trend	0.12	0.64	No trend	−0.06	0.83	No trend
Annual relative humidity	−0.43	0.06	No trend	−0.63	0.003	Decreasing	−0.64	0.003	Decreasing	−0.42	0.06	Decreasing

trends, while the average temperature of summer and spring had no trend. Kendall's statistics (T) for the mean temperature of annual, spring, summer, autumn, and winter were 0.64, 0.25, 0.34, 0.53, and 0.59, respectively. Therefore, the largest warming occurred in autumn ($T = 0.53$) and winter ($T = 0.59$) seasons (table 4). Moreover, there were significant increasing trends in annual mean minimum temperature, annual mean maximum temperature, annual absolute minimum temperature, and mean temperatures of January and February (Kendall statistics were 0.61, 0.60, 0.64, 0.42, and 0.48, respectively), whereas the annual absolute maximum temperature and the mean temperatures of July and August showed no trend. Among the studied months, the largest increase occurred in January temperature (tables 2 and 4). Moreover, the number of annual frost days showed a decreasing trend ($T = -0.63$) in the studied period (2006–2018).

Arak: the number of annual frost days and percentage of mean annual humidity showed decreasing trends ($T = -0.63$ and -0.48) in the studied period (2006–2018), whereas the annual absolute minimum temperature, annual mean minimum temperature, and the mean temperature of January showed increasing trends (Kendall statistics were 0.53, 0.41, and 0.45, respectively). Moreover, two peaks were observed in the studied period, the first one occurring from 2006 to 2012 and the second occurring from 2013 to 2018. Statistical analysis showed increasing trends in the mean temperatures of annual, minimum, maximum, January, and February (table 4).

Baft: in this station, the number of annual frost days and percentage of mean annual relative humidity showed decreasing trends ($T = -0.61$ and -0.64), whereas the other studied factors showed no trend in the studied period (table 4).

Najaf-abad: the number of annual frost days and percentage of mean annual humidity showed decreasing trends ($T = -0.61$ and -0.41), whereas the mean temperatures of annual, minimum, and January showed increasing trends ($T = 0.48$, 0.42, and 0.61) in the studied period (table 4).

Trends in the population of the leopard moth

In Saman and Najaf-abad stations, significant increases were observed in the mean number of moths caught (in each trap), the percentage of infested branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) during the studied years (2006–2018). The Kendall statistics in the Saman station were calculated as 0.59, 0.66, 0.79, and 0.98, respectively, whereas in the Najaf-abad they were 0.90, 0.90, 0.68, and 0.98, respectively (table 5).

In Arak, the mean number of moths caught (in each trap), the percentage of infested branches/tree (in August), the number of active galleries/tree (in November), and the infested areas (ha) showed increasing trends (Kendall statistics were 0.76, 0.58, 0.55 and 0.73, respectively). In the Baft station, the infested areas (ha) showed an increasing trend, whereas there was no trend for the mean number of moths caught (in each trap). Moreover, a decreasing trend was observed for the percentage of infested branches/tree (in August) and the number of active galleries/tree (in November) (table 5).

Relation between climate factors and population and damage of *Z. pyrina*

Saman (Chaharmahal va Bakhtiari province): according to the results, there was a positive and significant relation between

Table 5. Mann–Kendall trend analysis of time series data of *Z. pyrina* L. population and damage for the time period 2006–2018

	Saman			Arak			Baft			Najaf-abad		
	Kendall's statistics (T)	*P*-value	Trend	Kendall's statistics (T)	*P*-value	Trend	Kendall's statistics (T)	*P*-value	Trend	Kendall's statistics (T)	*P*-value	Trend
No. of moths caught	0.59	0.009	Increasing	0.76	0.0001	Increasing	0.26	0.27	No trend	0.90	0.0001	Increasing
Infected branches (%)	0.66	0.004	Increasing	0.58	0.04	Increasing	−0.67	0.003	Decreasing	0.90	0.0001	Increasing
No. of active galleries	0.79	0.0001	Increasing	0.55	0.02	Increasing	−0.77	0.001	Decreasing	0.68	0.004	Increasing
Infested areas (ha)	0.99	0.0001	Increasing	0.73	0.001	Increasing	0.94	0.0001	Increasing	0.098	0.0001	Increasing

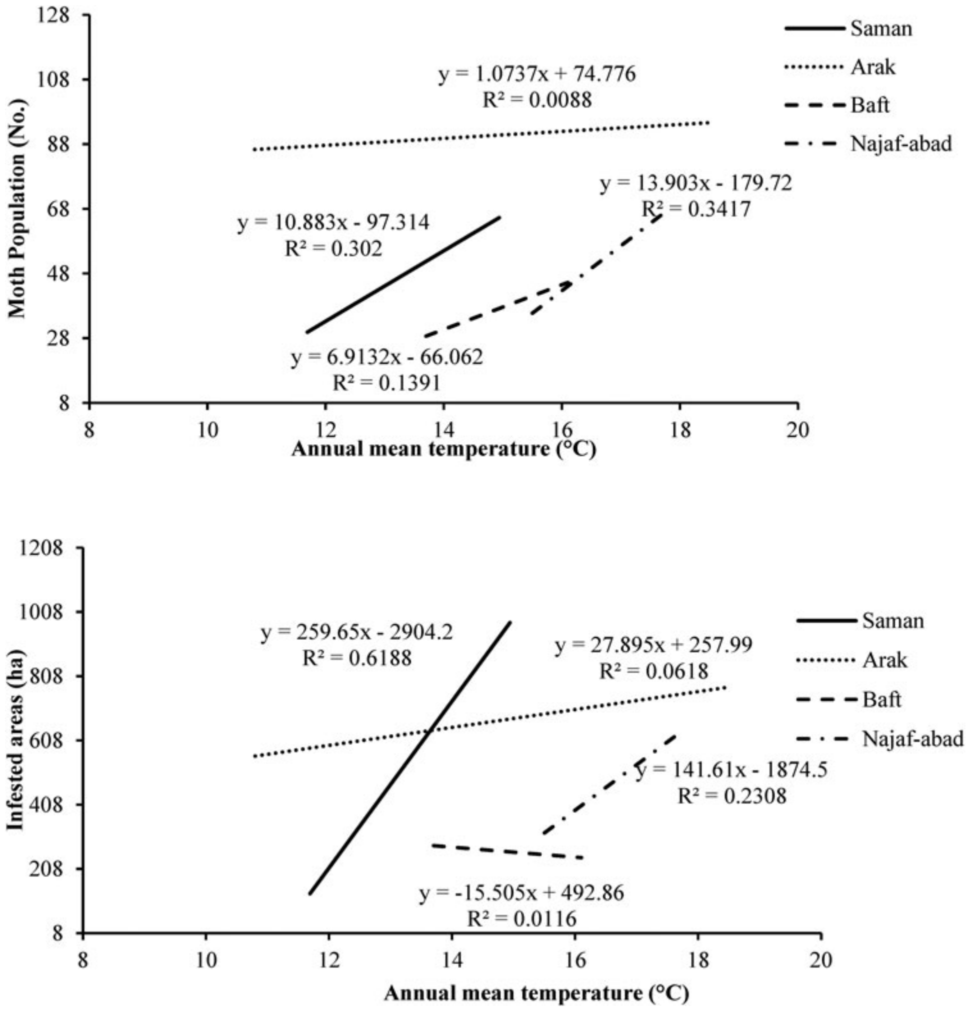

Figure 1. Relation between annual mean temperature and population and damage of *Z. pyrina* L. in the studied areas.

the number of trapped male moths and temperature (especially the annual mean temperature, annual mean maximum temperature, mean temperature of January, autumn, and winter seasons), while negative and significant relations were observed between the pest population and the number of frost days ($r = -0.52$) and the annual relative humidity ($r = -0.80$). Moreover, increasing annual absolute minimum ($r = 0.69$) and absolute maximum temperatures ($r = 0.78$) had positive and significant effects on the percentage of infested branches (figs 1–4).

The relation between the number of active galleries/tree (in November) and the number of frost days ($r = -0.56$) and the annual relative humidity ($r = -0.74$) was significantly negative, whereas the relation between the number of active galleries/tree and the temperature variables (including annual mean temperature, annual mean maximum temperature, the average temperature of January, autumn, and winter seasons) were significantly positive. The pest-infested area was positively correlated with temperature (especially the annual absolute minimum temperature, mean annual temperature, mean maximum temperature, and average temperatures of January, February, autumn, and winter) and negatively correlated with frost days and relative humidity.

Stepwise regression analysis showed that among the different climate variables, the mean temperature of January and mean annual humidity were the most statistically significant variables on the number of trapped male moths ($r = 0.88$, $r^2 = 0.77$, $F(2, 8) = 13.52$, sig. 0.003) and number of galleries/tree ($r = 0.85$, $r^2 = 0.73$, $F(2, 8) = 10.87$, sig. 0.005). Moreover, the mean temperatures of January and autumn, and annual mean maximum temperature ($r = 0.99$, $r^2 = 0.98$, $F(3, 7) = 100.48$, sig. 0.0001) were most closely related to the percentage of infested branches, while the area of infested orchards (ha) was most closely correlated with the annual absolute minimum temperature ($r = 0.72$, $r^2 = 0.52$, $F(1, 9) = 9.88$, sig. 0.012).

Baft (Kerman province): there was no significant relation between mean temperature (annual, maximum, and minimum) and the pest population and damage, whereas the number of frost days ($r = -0.56$) and percentage of annual relative humidity ($r = -0.74$) were negatively correlated with the mean number of moths caught ($r = -0.48$ and $r = -0.76$), the percentage of infested branches/tree ($r = -0.58$ and $r = -0.63$), and the infested areas ($r = -0.68$ and $r = -0.70$, respectively) (figs 1–4).

In stepwise regression analysis, mean annual relative humidity and annual mean minimum temperature were most closely related to the number of trapped male moths ($r = 0.62$, $r^2 = 0.38$, $F(1, 10) = 6.13$, sig. 0.03) and the number of galleries/tree ($r = 0.82$, $r^2 = 0.67$, $F(1, 10) = 20.10$, sig. 0.001), respectively. Moreover mean temperature of January and mean annual relative humidity were most closely related to the number of infested branches/tree ($r =$

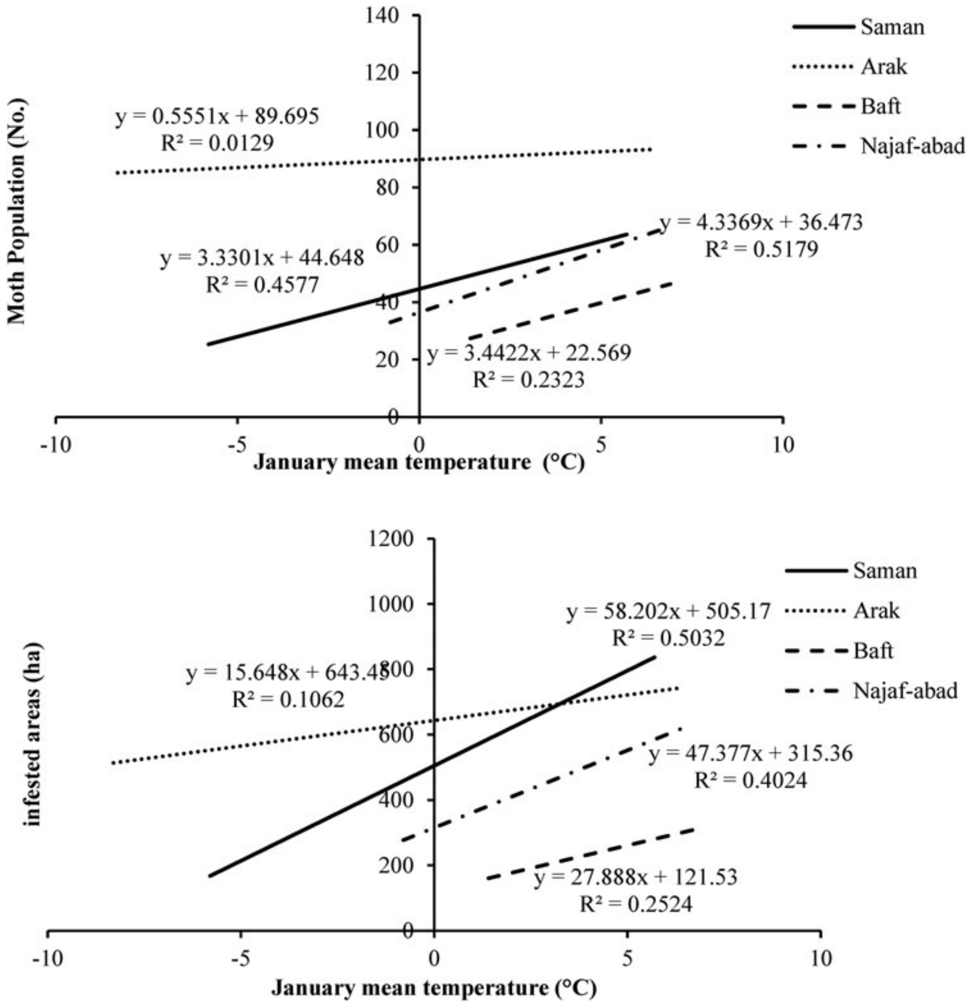

Figure 2. Relation between January mean temperature and population and damage of *Z. pyrina* L. in the studied areas.

0.91, $r^2 = 0.82$, $F(2, 9) = 20.10$, sig. 0.0001), whereas the annual mean maximum temperature was most closely related to the area infested ($r = 0.81$, $r^2 = 0.81$, $F(1, 10) = 43.92$, sig. 0.0001).

Arak (Markazi province): the relations of the mean number of moths caught (per trap), the percentage of infested branches/tree, the number of active galleries/tree, and the infested areas with the number of frost days ($r = -0.55$, -0.66, -0.56, and -0.61) and annual relative humidity ($r = -0.85$, -0.62, -0.78, and -0.73, respectively) were significantly negative. Moreover, by increasing the temperature (especially the annual mean temperature, the annual mean maximum temperature, the mean temperature of January and February), the number of active galleries/tree, and the infested areas were significantly increased (figs 1–4). The number of frost days was the most significant variable fitting the regression model of *Z. pyrina* infested areas ($r = 0.67$, $r^2 = 0.44$, $F(1, 10) = 7.96$, sig. 0.018).

Najaf-abad (Isfahan province): there were negative and significant relations between the number of trapped male moths and the number of frost days ($r = -0.61$) and per cent of annual relative humidity ($r = -0.56$). Moreover, the relations of mean annual relative humidity with the percentage of infected branches/tree ($r = -0.69$), the number of active galleries/tree ($r = -0.53$), and the infested areas ($r = -0.93$) were significantly negative. Moreover, mean temperatures of annual, minimum, and January had significant and positive correlation with the population, damage (per cent of infected branches and the number of active galleries/tree), and infestation area of *Z. pyrina* (figs 1–4). According to stepwise regression analysis, the mean temperature of January was the best-fitted variable in regression models of the number of trapped male moths ($r = 0.73$, $r^2 = 0.54$, $F(1, 10) = 11.72$, sig. 0.007) and the number of infested branches/tree ($r = 0.72$, $r^2 = 0.52$, $F(1, 10) = 10.74$, sig. 0.008), whereas the mean annual relative humidity was most closely related to the number of active galleries/tree ($r = 0.59$, $r^2 = 0.34$, $F(1, 10) = 5.28$, sig. 0.04). For the pest-infested areas (ha), the mean temperature of January, and annual absolute maximum temperature had the strongest relationship ($r = 0.83$, $r^2 = 0.69$, $F(2, 9) = 9.81$, sig. 0.005).

At a result, among the studied climate factors, the mean temperature of January, the mean temperatures of autumn and winter seasons, and the annual mean maximum temperature had positive correlations with *Z. pyrina* population size and damage in the walnut orchards, whereas percentage of relative humidity and the number of frost days had negative correlations.

Discussion

Climate factors, temperature and precipitation in particular, have strong influences on the development, reproduction, and survival

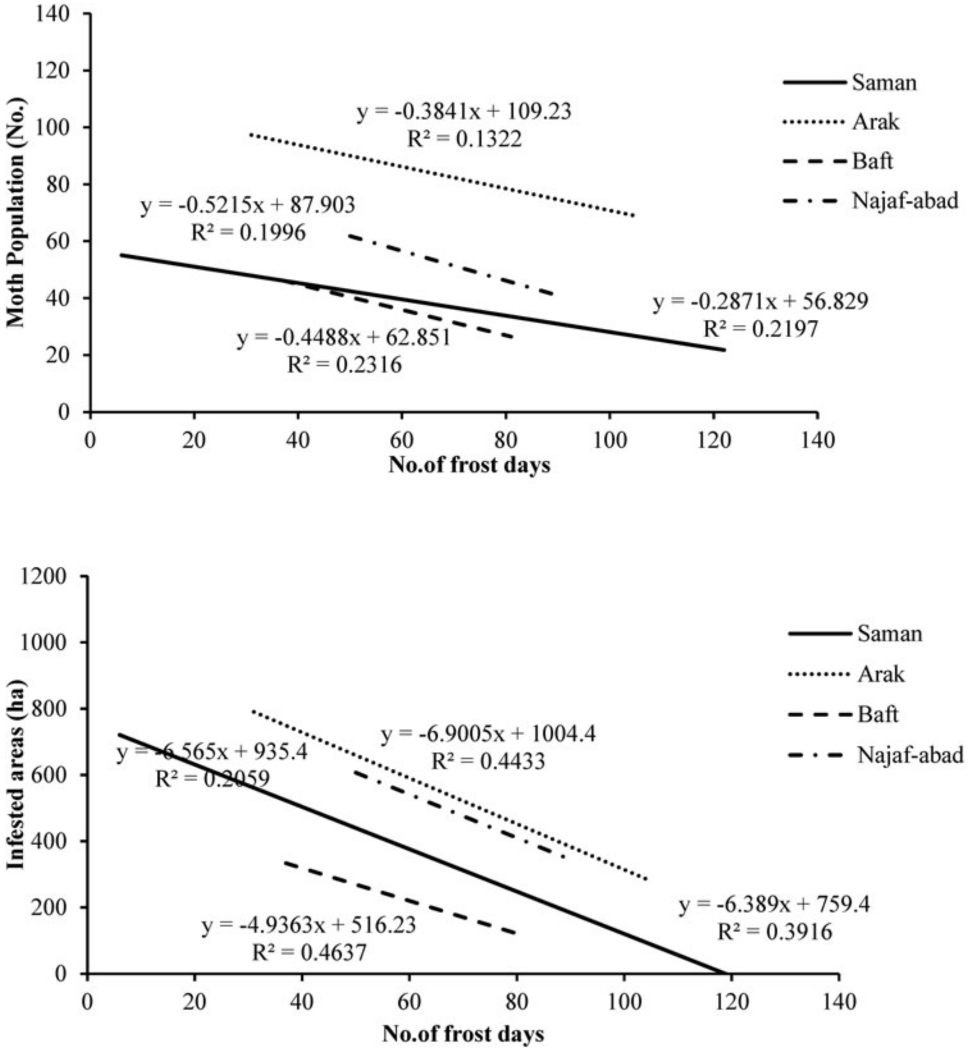

Figure 3. Relation between the number of frost days and population and damage of *Z. pyrina* L. in the studied areas.

of insect pests; therefore these organisms are affected by any change in the climate factors (Petzoldt and Seaman, 2006; Skendžic *et al.*, 2021). Our results suggested that climate factors strongly affected the population and damage of *Z. pyrina* in the studied areas. The pest population significantly increased with increasing temperature and decreasing relative humidity and number of frost days. It was reported that climate factors (especially temperature, precipitation, and humidity) were the most important factors which influence insects' and mites' life-table parameters, their distribution, and seasonal activity under field conditions (Ullah *et al.*, 2012; Bayu *et al.*, 2017; Islam *et al.*, 2017; Saeidi and Nemati, 2017, 2020; Shimazaki *et al.*, 2019). Moreover, they indirectly influence the pests through changes in the physiology or existence of their host plants (Prakash *et al.*, 2014). Rouault *et al.* (2006) reported that populations of bark beetles (*Ips typographus* L. and *Pityogenes chalcographus* L.) in the Western Europe forest were positively influenced by prolonged water stress and high temperatures and indirectly through physiological changes and decline of host resistance. According to Yihdego *et al.* (2019), plants stressed by drought are more susceptible to insect attack because of a decrease in the production of secondary metabolites that have a defence function. In another study, Ahmed *et al.* (2012) reported that climate factors such as temperature, relative humidity, and sunshine hours were positively related to the infestation of red spider mites in Bangladesh tea orchards, whereas heavy rainfall, cloud coverage, and water requirement of the crop were negatively correlated with the mite infestation. Moreover, the effect of changes in temperature and humidity was reported on the development and outbreak of spider mites (Mandal *et al.*, 2006; Kumar *et al.*, 2015), bark beetles (Bentz *et al.*, 2010; Yihdego *et al.*, 2019), whiteflies (Pathania *et al.*, 2020), *T. tabaci* (Bergant *et al.*, 2005), and peach twig borer, *A. lineatella* (Saeidi, 2019; Erhaft *et al.*, 2021).

Our results indicated significant trends in the studied climate factors during 2006–2018. Mean temperatures of annual, different seasons, and months showed significant and increasing trends, whereas the number of annual frost days indicated a decreasing trend. Trend analysis is one of the most important statistical methods used to evaluate the potential effects of climate change on time series data (such as temperature, precipitation, population, etc.). In this study, we used the Mann–Kendall method which is a non-parametric statistical test proposed by the World Meteorological Organization in trend analysis of climate series (Nicholson and Palao, 1993; Xu *et al.*, 2003; Pohlert, 2016).

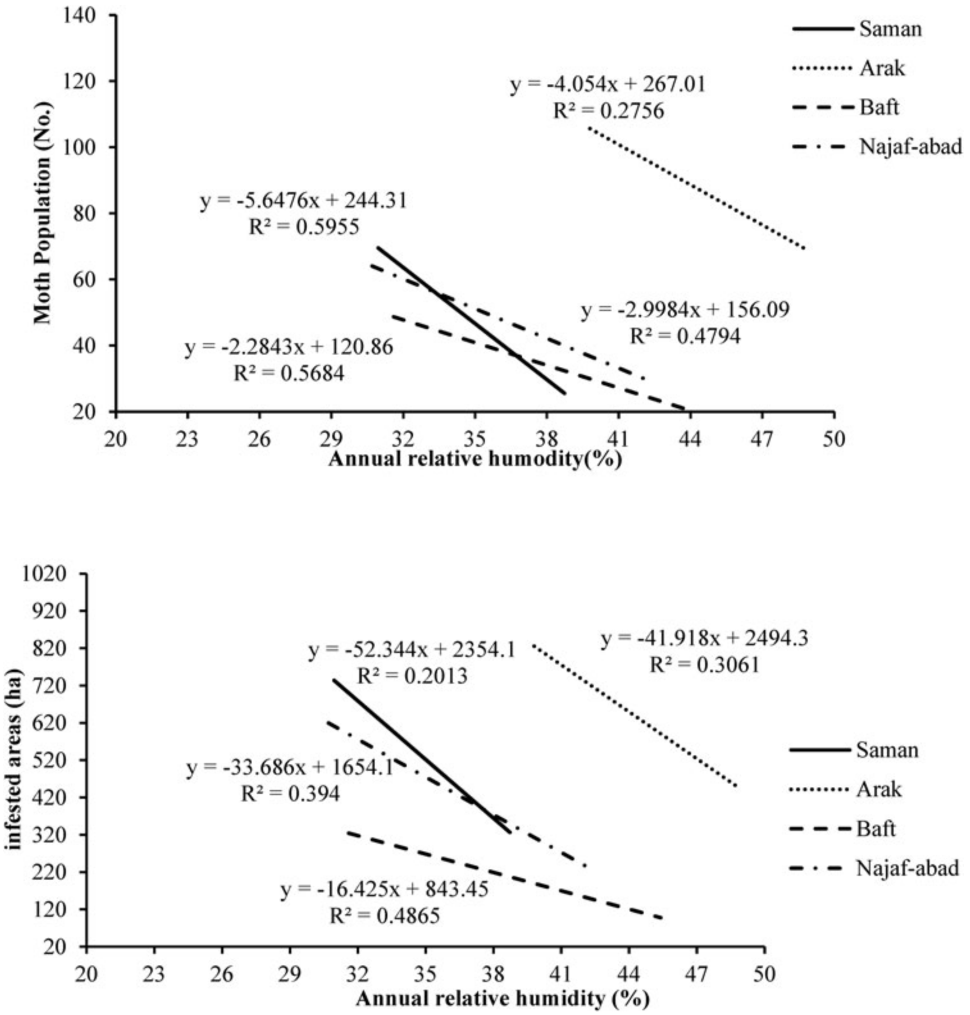

Figure 4. Relation between annual relative humidity and population and damage of *Z. pyrina* L. in the studied areas.

The phenomenon of climate change and increasing temperature, or global warming, is due to human activities which produce greenhouse gases (IPCC, 2022). The global annual temperature has increased at an average rate of 0.2–0.3°C per decade over the 20th century; therefore the Earth could experience global warming of 1.4–5.8°C over the next century (IPCC, 2022). Our results indicated an increasing trend in the temperature of the studied meteorological synoptic stations during the studied period (2006–2018). According to Skendžic *et al.*, (2021) global climate warming could trigger an expansion of insect geographic range, increased overwintering survival, increased number of generations, increased risk of invasive insect species, and insect-transmitted plant diseases, as well as changes in their interaction with host plants and natural enemies (Skendžic *et al.*, 2021).

Among the studied temperature variables, increasing the minimum temperature (especially in the winter and autumn seasons) appears to be an important factor influencing *Z. pyrina* population. Hill (1987) reported winter as the most critical season for many insect pests, as low temperatures can significantly increase mortality and thus reduce populations in the following season (Hill, 1987). Studies have shown that global warming is most pronounced in winter at high latitudes (Pachauari and Reisinger, 2007). Therefore, insects that undergo winter diapause are experiencing the greatest changes in their thermal environment (Bale and Hayward, 2013). *Z. pyrina* overwinters as larvae inside the trunk and the main branches of walnut trees (Radjabi, 2002; Kolyaee and Hassani, 2014), therefore, winter mortality is critical in the transition to the next generations. According to Reddy *et al.* (2015), the warmer winter reduces the mortality of the cotton bollworm, *Helicoverpa armigera* Hübner, over-wintering stages, and as a result, its population increases sharply in the next season. Based on the evidence obtained from fossils, the insect species diversity and their feeding intensity have a direct relationship with temperature (Kujawski, 2011). Another effect of rising temperature is on biological activities and the number of pest generations. Saeidi et al. (2022) showed that *Z. pyrina* could complete its life cycle within a year in Chaharmahal va Bakhtiari province, Iran. According to other researchers, some individuals require 1 year but others may require 2 years to complete their development (Esmaili, 1991; Radjabi, 2002; Kutinkova *et al.*, 2009; Kolyaee and Hassani, 2014; Hegazi *et al.*, 2015; Besharatnejad *et al.*, 2016). Our results showed the increasing autumn temperature allows *Z. pyrina* larvae to feed until the end of November and warmer winter increases their survival. Moreover, increasing the spring and summer temperatures favour faster development and emergence of *Z. pyrina* adults. According to reports, temperature is the most important climate variable that affects the behaviour, population dynamics, distribution, growth and development, survival, and reproduction of insects and mites (Petzoldt and Seaman, 2006; Skendžic *et al.*, 2021). Rising temperatures may increase the survival of overwintering stages of insects at higher altitudes, and lead to the expansion of their geographic range (Pareek *et al.*, 2017).

Our results demonstrated that the area (ha) infested by *Z. pyrina* significantly increased from 2006 to 2018. According to FAO (2020), climate change creates new ecological niches that provide opportunities for insect pests to establish and spread in new geographic regions and shift from one region to another. The spread of crop pests across physical and political boundaries increases the percentage of crop losses and threatens food security in different parts of the world (Fand *et al.*, 2012; FAO, 2020). For many pest species, a pole-ward shift in distribution is predicted as a response to global warming (Bebber *et al.*, 2013, Fekrat and Farashi, 2022). For example, in Europe, the European corn borer (*Ostrinia nubilalis* Hubner) has shifted more than 1000 km northwards (Porter *et al.*, 1991), and the pink bollworm, *Pectinophora gossypiella* Saunders (Gutierrez *et al.*, 2006) and the olive fly, *Bactrocera oleae* Rossi (Gutierrez *et al.*, 2009) are expanding northwards due to the effects of increasing temperatures in Europe and America. According to Fekrat and Farashi (2022), under future climate conditions, the risk areas of *Z. pyrina* in the Northern and Southern Hemispheres are expanding northwards and southwards, respectively.

In conclusion, climate variables especially rising temperatures appears to strongly impact the population and damage of *Z. pyrina* in walnut orchards. Therefore, our findings are useful for agricultural experts and farmers to predict the pest population and damage in the next years under climate change scenarios and develop a successful integrated *Z. pyrina* management programme to reduce the pest-induced crop losses. Moreover, knowledge about changes in seasonal activity, population dynamic, and distribution of *Z. pyrina* are necessary to develop more efficacious control methods such as pheromone traps (for monitoring, mass trapping, or mating disruption), cultural techniques (decreasing drought stress and time of removing infested branches), and insecticides application at the proper time and dosage. According to Skendžic *et al.*, (2021) and Fekrat and Farashi (2022), as climate change exacerbates the pest problem, there is a great need for developing new pest management strategies in the future. These include the development of more efficacious integrated pest management tactics, monitoring climate and pest populations, and the use of modelling prediction tools.

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Author contributions. Z. S. designed the experiments, analysed data, and wrote the manuscript. Material preparation and data collection in Chaharmahal va Bakhtiari, Kerman, Isfahan, and Markazi provinces were performed by Z. S., H. Z., M. H. B.-N., and M. Y., respectively. The authors read and approved the manuscript.

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