J Pest Sci
DOI 10.1007/s10340-017-0899-z

ORIGINAL PAPER

Biological parameters of the invasive brown marmorated stink bug, *Halyomorpha halys,* in southern Europe

E. Costi[1] · T. Haye[2] · L. Maistrello[1]

Received: 30 January 2017 / Revised: 18 June 2017 / Accepted: 21 June 2017

Abstract The brown marmorated stink bug, *Halyomorpha halys*, is an invasive pest species, first detected in Italy in 2012. Only 2 years after this first detection, increasing damage was reported in fruit orchards in the Emilia Romagna region, the first invaded area, which is one of the most important regions for the Italian and European fruit production. In the present study, life table parameters of *H. halys* populations were investigated in Italy under typical temperate/Mediterranean climate conditions representative of southern Europe. Our findings indicate that in Italy *H. halys* has two generations/year and very high reproductive rates for both generations ($R_0 = 24.04$ and 5.44 for the overwintering and summer generation, respectively). The huge growth rates explain why in 2015 a massive outbreak of *H. halys* was observed in Italy, and these rates confirm that the pest is a threat for agricultural production in southern Europe. The parameters obtained in this study are essential for the development and optimization of sustainable management strategies.

Communicated by M. Traugott.

Special Issue: The brown marmorated stink bug *Halyomorpha halys* an emerging pest of global concern.

Electronic supplementary material The online version of this article (doi:10.1007/s10340-017-0899-z) contains supplementary material, which is available to authorized users.

✉ E. Costi
elena.costi@unimore.it

[1] Dipartimento di Scienze della Vita, Università di Modena e Reggio Emilia, Via G. Amendola 2, 42122 Reggio Emilia, Italy

[2] Centre for Agriculture and Biosciences International (CABI), Rue des Grillons 1, Delémont 2800, Switzerland

Keywords Alien species · Life table · Fecundity · Phenology · Growing population · Bivoltinism

Key messages

- *Halyomorpha halys* is an invasive alien species detected for the first time in Italy in 2012.
- A life table study was performed in outdoor conditions in the region of first occurrence.
- The obtained biological parameters indicate bivoltinism and very high growth rates in Italy.
- New knowledge on the phenology and population growth will help to develop tools for the sustainable management of *H. halys* in southern Europe.

Introduction

Invasive alien species adversely impact biodiversity and related ecosystem services, causing a multitude of negative effects on natural and agricultural ecosystems, resulting in heavy economic losses worldwide (Simberloff et al. 2013). Among the invasive insect species, the brown marmorated stink bug (BMSB), *Halyomorpha halys* (Stål, 1855) (Heteroptera, Pentatomidae), is among the most threatening pests for many agricultural crops. It has a highly invasive behaviour, a rapidly expanding range throughout the world (Zhu et al. 2016) and an elevated damaging potential because of its extremely wide host range that includes a variety of fruit, vegetable and row crops, as well as ornamental and non-crop plants (Leskey et al. 2012a; Lee et al. 2013; Rice et al. 2014; Bakken et al. 2015; Bergmann et al. 2016). Damage to host plants is caused by both adults and nymphs by piercing the surface injecting digestive enzymes and sucking plant fluids (Rice et al. 2014). In fruits, feeding injuries include deformities, scars, discolorations and pitting that render them unmarketable. Moreover, it is also a household nuisance pest due to its massive overwintering aggregations inside buildings (Inkley 2012). Native to eastern Asia (Lee et al. 2013), the BMSB was reported for the first time outside of its native area in Allentown, PA (USA), in the mid-1990s (Hoebeke and Carter 2003). Currently, *H. halys* occurs in 42 states of the USA (USDA-NIFA SCRI 2017) and in three Canadian provinces (Gariepy et al. 2014). In Europe, it has been reported in Switzerland in 2007 (Wermelinger et al. 2008), but the oldest records date back to 2004 (Haye et al. 2015). In recent years, it was also reported from many other countries, such as Liechtenstein, Germany, northern France, Hungary, Greece, Romania, Austria, Serbia, Russia, Spain, Bulgaria (Arnold 2009; Heckmann 2012; Callot and Brua 2013; Vetek et al. 2014; Milonas and Partsinevelos 2014; Macavei et al. 2015; Rabitsch and Friebe 2015; Šeat 2015; Mityushev 2016; Dioli et al. 2016; Simov 2016). In Italy, it was first discovered in the province of Modena (Emilia Romagna region, northern Italy) in 2012 (Maistrello et al. 2016b). To date, it is widespread in the northern Italian regions, with increasing occurrences in central Italy (Bariselli et al. 2016) and occasional detections in southern regions, including the islands Sardinia and Sicily (Dioli et al. 2016; Maistrello et al. unpublished data).

In the native areas, BMSB is considered an occasional pest in fruit orchards and soybean (Lee et al. 2013), but it has been much more destructive in the USA, the first country to which it was accidentally introduced in. Indeed, in the Mid-Atlantic region of the USA it took 15 years from its detection until it became a key pest in fruit orchards, e.g. *Prunus persica* (L.) Batsch, *Pyrus communis* (L.) and *Malus domestica* Borkh. (Leskey et al. 2012b), causing millions of dollars of losses (United States Apple Association 2010) and, as it spread across other regions, it also turned into a serious pest of vegetables, soybean and corn (Koch and Rich 2015; Philips et al. 2016; Rice et al. 2014; Venugopal et al. 2015). Its current management, consisting of season-long repeated insecticide treatments, has disrupted previous IPM programs (Leskey et al. 2012b).

The first records of BMSB in Italy occurred in Emilia Romagna, one of the most important fruit-producing regions of Europe, with a surface of 63.893 ha and an annual fruit production of 1,335,607 tons (Fanfani and Pieri 2016). After only 2 years since its first detection, fruit injuries were reported in this area, especially in privately owned, untreated orchards (Maistrello et al. 2016a). During summer 2015, a massive outbreak occurred, and serious economic damage (more than 50% deformed fruits) was recorded at harvest in commercial pear orchards (Maistrello et al. 2017). These facts elicited a major concern for the Italian agricultural production, and the recent detections in Greece (Milonas and Partsinevelos 2014), southern France (Maurel et al. 2016) and southern Spain (Dioli et al. 2016) raised a concrete risk that BMSB could become a serious agricultural pest in southern European countries along the Mediterranean basin. On the other hand, in Switzerland, located in the oceanic climate zone with warm summers, cool winters and high rainfalls, it only occasionally causes damage in private gardens. Remarkably, no severe economic damage has yet been reported in field crops, although *H. halys* has been present since more than 12 years (Haye et al. 2014).

The biology of BMSB was investigated in Asia (Lee et al. 2013) and the USA, but to date the only investigations in Europe were performed in the temperate regions of northern Switzerland (Haye et al. 2014). Here we present a study on the life table parameters of BMSB in the place of first detection in Italy, which in contrast to Switzerland is characterized by a temperate/Mediterranean climate, representative of southern European and Mediterranean countries.

Materials and methods

The study was performed under outdoor conditions in Sassuolo (Modena Province) (44°31′59.4″N 10°47′03.9″E), in an open wooden shed that provided shelter from weathering, e.g. direct sunlight and heavy rain, but would expose the bugs to outdoor conditions (photoperiod, temperature and relative humidity).

From October to December 2014, 1367 *H. halys* adults (712 males and 655 females) were collected during visual inspections of green houses, barns, garden sheds and individual homes located in Modena and Reggio Emilia provinces (northern Italy). A minimum of 150 males and 150 females was then placed in each of the four wooden cages (24 × 26.5 × 19 cm). The wooden cages were filled with cardboard panels separated by 1 mm in order to provide a representative overwintering site. Each cage had a slit at the base (5 mm wide), allowing adults to exit cages in the spring. To be able to monitor adult emergence after overwintering and to prevent the escape of adults, each wooden cage was placed inside a plastic box (50 × 40 × 25 cm) with fine mesh windows on all sides. A data logger (Escort I-Mini) was placed inside one of the plastic boxes for temperature and humidity recording. Starting January 2015, every 48 h the bugs found in the plastic box, which had come out from the wooden cages, were recorded and sexed. These adults were left in the plastic box, but were individually marked with water-based colours to be able to distinguish them from newly emerging adults. This allowed obtaining the number of bugs that successfully overwintered but died before reproduction. The overwintering survival was evaluated after counting the dead specimens inside the wooden cages 2 weeks after the exit of the last bug. Upon detection in the plastic box, the successfully overwintered adults were immediately transferred in a similar plastic box used for rearing, which was provided with organic peanuts, fresh organic green beans and carrots and *Peperomia obtusifolia* as food sources, and plastic vials filled with wet cotton as water source (Medal et al. 2012). Food and water were replaced twice a week.

In spring, ten adult couples were randomly chosen from the rearing box, when they were observed mating and then placed in individual, ventilated plastic containers (12 cm diameter, 24 cm height) exposed to the outdoor conditions and fed as previously described. From May 1 onwards, 1 week after the highest exit of overwintering adults had been observed, the selected couples were monitored daily for oviposition and mortality. Newly laid egg masses were removed immediately from the adult containers and placed individually in smaller sealed ventilated plastic containers (6.8 cm diameter, 12 cm height), which were kept under outdoors conditions. Eggs were counted and observed daily from hatching to the appearance of the 2nd instar, recording the number of hatched eggs, juvenile nymphs and nymphal mortality. Ten 2nd instar nymphs were then randomly selected from the first four egg masses laid in each week. When less than 4 egg masses per week were laid, all egg masses laid in that week were kept, and the development of all hatching nymphs was followed. The selected 2nd instar nymphs were moved to bigger ventilated sealed plastic containers (12 cm diameter, 24 cm height), and their development was monitored daily, recording the number of emerging and dying individuals in each stage until reaching adulthood. Newly emerged adults of the summer generation were sexed and coupled ($n = 15$), and these adults and their offspring were followed as previously described for the overwintered adults. Newly emerged adults of the following generation were sexed and coupled again to verify whether they could produce a third generation or go into diapause. For the purpose of this work, the overwintering generation is represented by the individuals that emerge in late summer, enter overwintering and then produce the summer generation in the following year. The summer generation is represented by the individuals emerging in mid-summer that will generate the overwintering individuals.

Life table parameters

In order to estimate the generational mortality rate, life tables were constructed for the overwintering and summer generation, using the data from the experiments described above. Since from the second instar onwards not all individual nymphs were followed throughout the season, selected subgroups of nymphs were only representatives for each cohort. The *observed* mortalities of nymphs (N2–N5) in the experimental study were then applied to the *actual* number of eggs laid during each time period (cohort) (Haye et al. 2014).

In order to evaluate the generation mortality rate, the unknown mortality factor (e.g. food quality) and the mortality attributable to local climatic condition were estimated as apparent mortality, real mortality, intensity of mortality (k values) and generational mortality (Bellows et al. 1992). The apparent mortality (q_x) is calculated as a fraction of died in a specific stage (d_x) out of the total number of individuals entered in the same stage (l_x). The real mortality (r_x) is expressed as a fraction of dead in each stage (d_x) out of the total number of *H. halys* eggs ($l_0 = 2852$ for the overwintering generation; $l_0 = 2430$ for summer generation) at the beginning of the life table ($r_x = d_x/l_0$). The k_s values are the intensity of mortality which is a measure of mortality independently from the individual number, i.e. $k_x = -\log\ (1 - m_x)$. The k_x values are expressed as proportions of the generational mortality K_s, which is the sum of all k_x values. The proportion of the total generational mortality by the mortality in a particular stage is expressed as 100 k_x/K_s. This value shows the impact of mortality by the local climatic conditions in each stage on the generational mortality of *H. halys*. The population growth of *H. halys* in the overwintering and summer generation is described by the net reproductive rate of increase (R_0), which shows the number of times the stink bug population increases or decreases from one generation to the next (Van Driesche et al. 2008). Growing populations have R_0 values greater than one, whereas R_0 values less than 1 show that the population is declining. The values for R_0 were calculated from the realized progeny divided by the number of eggs in the overwintering and summer generation ($l_0 = 2852$; $l_0 = 2430$).

Results

The first adults came out from the overwintering cage at the end of January, but these early emerging adults all died within the first week of February. The successful exit from overwintering was observed from March 27 onwards, when daily maximum temperature exceeded 14 °C, and lasted until May 23. The peak of exiting adults as well as the first mating was observed during the second week of May, when the mean daily temperature exceeded 21 °C. In total, 28% of adults survived overwintering, but only half of them (14%) were able to survive until reproduction (=86% total overwintering mortality). In the overwintering generation, the time elapsed between the exit from overwintering and the first egg laying was on average 35.8 ± 4.29 SE days, whereas in the summer generation the time elapsed from adult emergence and the first oviposition was on average only 12.31 ± 0.89 SE days. Overwintered adults laid their first egg mass in mid-May and continued until mid-August, whereas the oviposition period of the new summer generation ranged from mid-July to the first week of September (Fig. 1). Among the overwintered couples ($n = 10$), the peaks of egg laying were observed from mid-June to mid-July, when the mean temperatures were 23.5 and 28.4 °C, respectively (ESM Table 1). In the summer generation ($n = 15$), these peaks were observed from late July to mid-August, with mean daily temperature of 28.65 and 27.8 °C, respectively (ESM Table 2). In the overwintering generation, a decrease in the number of eggs/female was observed from the last week of July onwards, when temperatures ranged from 24.9 to 28.6 °C. A similar trend was observed in the summer generation, when oviposition declined from the second week of August onwards. Considering the overall oviposition period, the oviposition peak (767 eggs/week) was observed in the 29 to 30 calendar week (20–26 July) due to the overlap of the oviposition period of both generations. In our experiments, all overwintered females ($n = 10$) laid eggs, with a realized mean lifetime fecundity of 285 ± 22.83 SE eggs per female. In contrast, 13 out of 15 females of summer generation laid eggs, with a mean realized lifetime fecundity of 214.69 ± 30.56 SE eggs per female. The number of egg masses laid by single overwintered females varied from 7 to 15, whereas in summer generation it was 2–15. There was no oviposition observed among adults developing from eggs of the summer generation, and thus, no third generation did develop. In 2015, the first nymphs emerged on May 29 from eggs laid May 21 and became adults on July 4, whereas the last nymphs of the overwintering generation emerged on August 18 and turned into adults on October 13. The overlapping of the two generations was observed starting July 19, when the first nymphs of second generation emerged. The last nymphs of the second generation emerged September 6, but they were not able to complete development. Moreover, none of the 2nd instar nymphs obtained from eggs of the summer generation past August 25, when the photoperiod changed from 14 to 13 h, ever reached adulthood. Overall mortality of eggs and nymphs varied between weekly cohorts (Tables 1, 2) and ranged from 10 to 100% and 39 to 68% in the overwintering and summer generation, respectively. Moreover, the overall mean mortality ranged from 25.67 ± 3.22 to 7.33 ± 2.74 and 33.89 ± 4.28 to 1.68 ± 1.68 in the overwintering and summer generation, respectively. In both generations, the highest mortality was observed in the egg stage.

Life table parameters

Overall, egg mortality contributed most to the generational mortality in the overwintering generation (36.98%, Table 3), whereas the mortality of diapausing adults (%) was the key factor contributing to the generational

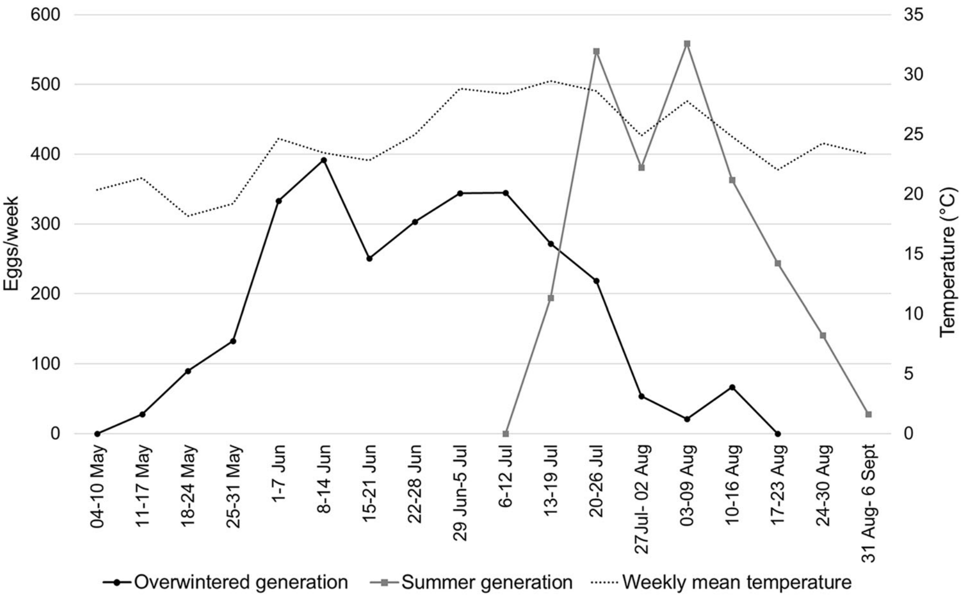

Fig. 1 Oviposition patterns of the overwintered and summer generations of *Halyomorpha halys* and mean weekly temperatures at Sassuolo (northern Italy) in 2015. For the two generations, 10 and 15 females were followed, respectively

Table 1 Observed mortality of eggs and nymphs produced by the overwintering generation of *H. halys* in Sassuolo (northern Italy) in 2015

Oviposition period	Eggs laid per week (e_x)	Proportion of total number eggs laid (%) ($e_x \times 100/E$)	% Mortality			% Mortality				% Total mortality
			Eggs	N1		N2	N3	N4	N5	
11–17 May	28	1	32.14	0	10	0	20	12.5	14.28	46.43
18–24 May	90	3.2	5.55	4.71	10	0	0	0	0	10
25–31 May	133	4.6	9.77	7.5	10	40	0	0	0	19.54
1–7 June	333	11.7	34.53	4.59	10	0	0	0	0	37.54
8–14 June	392	13.7	24.74	16.64	10	0	0	0	20	39.29
15–21 June	251	8.8	19.52	2.97	10	0	0	10	0	22.31
22–28 June	303	10.6	12.54	3.02	10	30	14.29	33.33	25	17.49
29 June–5 July	344	12	31.39	8.24	10	10	11.11	0	62.5	39.83
6–12 July	345	12	33.91	5.22	10	20	0	0	25	38.55
13–19 July	272	9.5	30.14	12.5	10	30	14.29	16.6	0	40.80
20–26 July	219	7.7	35.61	19.15	10	20	25	16.66	0	50.23
27–02 August	54	2	48.15	0	28	32.14	15.79	6.25	0	72.22
03–09 August	21	0.7	28.57	0	15	100	–	–	–	100
10–16 August	67	2.3	12.77	39.02	25	72	57.14	0	33.33	95.75
Mean (SE)			25.67 ± 3.22	8.83 ± 2.82		25.30 ± 7.97	12.12 ± 4.34	7.33 ± 2.74	13.85 ± 5.11	
Total (E)	2852									

mortality in the summer generation (65.33%, Table 4), when considering the potential population growth from 1 year to the next.

The total generational mortality was higher (97.47%, Table 4) in the summer generation than in the overwintering generation (56.46%, Table 3). The realized net reproductive rate (R_0) of the overwintering generation was 24.04, indicating strongly growing populations in the first half of the summer. In contrast, the growth rate of the new summer generation (from 2015 to 2016) was much lower (5.44) due to high losses during the overwintering period, but still is indicating growing populations. However, the life table presented here only considers climatic conditions as mortality factors and excludes any potential mortality by natural enemies. The total mortality was calculated using the formulas $l_0 - \mathrm{l}_{(\text{new generation adults})} \times 100/l_0$ and $l_0 - l_{x\ (\text{overwintering adults})} \times 100/l_0$ in Tables 3 and 4, respectively.

Discussion

The present life table study was performed in Emilia Romagna, a region located in the Po River Valley of northern Italy, and the findings are strikingly different from earlier studies conducted in Switzerland (Haye et al. 2014), just 400 km north of the study area. Compared to the strictly univoltine populations in northern Switzerland, our study indicates that south of the Alps BMSB has two generations/year, as observed in the Beijing Province in China (Zhang et al. 1993) and in the southern United States, e.g. Virginia and West Virginia (Leskey et al. 2012c; Bakken et al. 2015). According to Cesari et al. (2015), the BMSB population found in Emilia Romagna shares the same haplotype (H1) detected in most of the USA and in the Beijing area (Xu et al. 2014), which is different from the haplotypes that characterize the Swiss population (Gariepy et al. 2014). However, the observed differences clearly reflect the adaptation of this invasive pest to different climate and photoperiod conditions in both geographical regions. Due to warmer spring conditions, the first oviposition in Italy already occurred in mid-May, and the new generation adults emerged in the beginning of July, whereas in Switzerland oviposition did not start before mid-June and new adults did not occur before early August, when the photoperiod was already decreasing (≤15 h). In conclusion, adults of the summer generation need to emerge no later than the third week of July, when the photoperiod is still above 15 h, to be able to produce a

Table 2 Observed mortality of eggs and nymphs produced by the summer generation of *H. halys* in Sassuolo (northern Italy) in 2015

Oviposition period	Eggs laid per week (e_x)	Proportion of total number eggs laid (%) ($e_x \times 100/E$)	% Mortality		N2 followed	% Mortality				% Total mortality
			Eggs	N1		N2	N3	N4	N5	
13–19 July	194	7.98	24.23	26.53	10	10	0	0	0	44.84
20–26 July	548	22.5	41.97	9.75	10	20	12.5	0	0	48.18
27–02 August	381	15.68	43.83	11.21	10	10	11.11	0	0	50.66
03–09 August	559	23	46.51	11.37	10	40	33.33	0	0	62.08
10–16 August	363	14.94	41.05	47.93	10	30	57.14	0	0	47.93
17–23 August	244	10.04	33.60	7.41	10	0	20	0	0	39.34
24–30 August	113	4.65	29.20	1.64	60	40	11.11	40.63	11.76	68.14
31 August–6 September	28	1.15	10.71	0	0	24	5.26	10	–	67.86
Mean (SE)			33.89 ± 4.28	14.48 ± 5.56		21.75 ± 5.16	18.81 ± 6.51	6.33 ± 5.05	1.68 ± 1.68	
Total (E)	2430									

second generation within the same year, confirming findings from Yanagi and Hagihara (1980). In both regions, Italy and Switzerland, adults that emerged in the second half of August under short photoperiodic conditions (below 15 h light) went straight into diapause and did not show any oviposition behaviour.

In the Emilia Romagna region, the first cohort of overwintering adults that left their overwintering shelters in late January died almost immediately after its exit. Among all adults that successfully emerged from overwintering, only half were able to survive and reach the reproductive stage. According to Funayama (2012), adults that come out too early are those that have lower nutritional levels compared to the ones that come out later, and thus, they soon die in the absence of food. The overall overwintering mortality of 86% observed in Italy was much higher than that observed in Switzerland (39%) (Haye et al. 2014). The exit of the adults from the overwintering sites started when the maximum temperature exceeded 14 °C, with a photoperiod of 13 h, and lasted from late March to end of May. The same overwintering exit period was reported from northern Japan (Funayama 2012). In Emilia Romagna, the first egg masses were laid in mid-May when mean daily temperature was 21.35 °C and the photoperiod was approximately 15 h. The timing of the first egg laying agrees with observations in China (Wang and Wang 1988; Zhang et al. 1993), and Watanabe (1980) suggested that normal ovarian development occurs during photoperiods of $\geq$14 h. After the second week of July, adults of overwintering generation started to die and consequently oviposition by ageing females decreased. At the same time, the oviposition activity of the summer generation increased and the high number of egg masses found in the field in July can partially be explained by the overlapping oviposition periods of the two generations. Adults developing from eggs laid by the summer generation from July onwards did not form a third generation as reproductive diapause in these adults began from mid-August onwards, as suggested by Niva and Takeda (2003). In addition, nymphs that hatched after August 25 were not able to reach the adulthood due to the lack of required degree days (DD 117.65) needed to complete development (Haye et al. 2014).

Regarding sexual maturity, overwintered females needed on average 35.8 ± 4.29 (SE) days from exiting the overwintering sites to the first egg laying, whereas females of the summer generation laid the first eggs after 12.31 ± 0.89 (SE) days after emergence, which is in agreement with previous studies (Watanabe 1980; Yanagi and Hagihara 1980; Kawada and Kitamura 1983; Nielsen et al. 2008). The average fecundity of overwintered females (285 eggs) was 25% higher than the one of the summer generations (214 eggs). The oviposition period of the two generations lasted about 14 and 8 weeks for the

Table 3 Age-specific life table for the overwintered generation of *Halyomorpha halys* studied under outdoor temperatures in Sassuolo (northern Italy) in 2015

Overwintered generation stage	Stage		Apparent mortality	Real mortality (r_x)	k value	% of generational mortality 100 k_x/K_s
	l_x	d_x	$q_x(d_x/l_x)$	d_x/l_0		
Egg	2852	754.92	0.2647	0.265	0.134	36.98
N1	2097.08	211.60	0.1009	0.074	0.046	12.79
N2	1885.48	154.23	0.0818	0.054	0.037	10.26
N3	1731.25	192.34	0.1111	0.067	0.051	14.16
N4	1538.91	104.95	0.0682	0.037	0.031	8.49
N5	1433.96	192.29	0.1341	0.067	0.063	17.31
New generation adults	1241.67					
Sex ratio (% females)	0.5					
Adult females	620.84					
Realized fecundity	110.41					
Realized F_1 progeny	68,546.94					
R_0	**24.04**					
Total mortality	56.46%				$K_S = 0.362$	

Table 4 Age-specific life table for the summer generation of *Halyomorpha halys* studied under outdoor temperatures in Sassuolo (northern Italy) in 2015

Summer generation stage	Stage		Apparent mortality	Real mortality (r_x)	k value	% of generational mortality 100 k_x/K_s
	l_x	d_x	q_x (d_x/l_x)	d_x/l_0		
Egg	2430	998.24	0.4108	0.411	0.230	17.76
N1	1431.76	173.96	0.1215	0.072	0.056	4.32
N2	1257.80	172.95	0.1375	0.071	0.064	4.94
N3	1084.85	221.42	0.2041	0.091	0.099	7.64
N4	863.43	0.00	0	0	0	0.00
N5	863.43	0.00	0	0	0	0.00
Diapausing adults	863.43	740.30	0.8574	0.305	0.846	65.33
Overwintering adults	123.13					
Sex ratio (% females)	0.5					
Adult females	61.57					
Realized fecundity	214.69					
Realized F_1 progeny	13,218.46					
R_0	**5.44**					
Total mortality	97.47%				$K_S = 1.295$	

overwintered and summer generations, respectively. The observed fecundity values are in the range described by Kawada and Kitamura (1983) and Yanagi and Hagihara (1980). However, the fecundity of females was much higher than that reported from Switzerland (79.18), which may be related to temperature, the diet that was provided to the adults during the study or to genetic differences between *H. halys* populations.

The pest status of a species largely depends by the number of generations it can perform during the available growing season and by its fecundity. Apparently, the climatic conditions in northern Italy in 2015 were extremely favourable for *H. halys*. The realized net reproductive rates (R_0) of the Italian BMSB population were 24.04 and 5.44 for the overwintering and summer generation, respectively, indicating overall an extremely high growing potential of this pest. These growth rates may partially explain the very short time elapsed between the year of first discovery (2012) and the outbreak observed in the field in 2015, together with the detection of the first economic damage in the fruit orchards surrounding Modena (Maistrello et al. 2017). In addition, the high mobility of the adults (Wiman et al. 2014; Lee and Leskey 2015) and the movement of goods and materials containing overwintering adults by humans may have accelerated the fast dispersal of the pest in Italy (Maistrello et al., unpublished data). In contrast, the low impact of *H. halys* on crops in northern Switzerland is likely related to the univoltinism and the much lower growth rate of *H. halys* in this region ($R_0 = 5.69$; Haye et al. 2014).

The biological parameters presented in this study were obtained during only 1 year, and it is likely that population growth will fluctuate from year to year due to different temperature conditions. In particular, lower temperatures during summer may negatively affect the survival of the different instars, and adults may not reach their full reproductive potential. Furthermore, the impact of natural enemies was not measured in this study, and thus, the growth rates of the populations may be slightly overestimated. Nevertheless, the data from the outbreak year 2015 demonstrate impressively the huge growing potential of *H. halys* populations in favourable years in southern Europe. Furthermore, the present study provides important baseline data that can be used for the development of a decision support system and the optimization of management strategies for southern European countries along the Mediterranean basin, where most of the European fruit and vegetable production is located (EUROSTAT 2017).

Author contribution

TH and LM conceived and designed the study. EC conducted all experimental work. TH elaborated the life table data. All authors wrote and approved the manuscript.

Acknowledgements This research was partially supported by the grant 'Innovative tools and protocols for monitoring and sustainable control of the alien stink bug *Halyomorpha halys,* a new phytosanitary threat, and of other harmful heteropterans for the fruit crops of the territory of Modena' (2013.065) of 'Fondazione Cassa di Risparmio di Modena'. We are also grateful to the UNIMORE students Giulia Pinotti and Valentina Mammi who helped with the experimental work.

Compliance with ethical standards

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

Ethical approval This article does not contain any studies with human participants or animals (vertebrate) performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study

References

Arnold K (2009) *Halyomorpha halys* (Stål, 1855), eine für die europäische fauna neu nachgewiesene wanzenart (Insecta: Heteroptera, Pentatomidae, Pentatominae, Cappaeini). Mitteilungen Thüring Entomol 16:19

Bakken AJ, Schoof SC, Bickerton M et al (2015) Occurrence of brown marmorated stink bug (Hemiptera: Pentatomidae) on wild hosts in nonmanaged woodlands and soybean fields in North Carolina and Virginia. Environ Entomol 44:1011–1021. doi:10.1093/ee/nvv092

Bariselli M, Bugiani R, Maistrello L (2016) Distribution and damage caused by *Halyomorpha halys* in Italy. EPPO Bull 46:332–334. doi:10.1111/epp.12289

Bellows TSJ, Van Driesche RG, Elkinton JS (1992) Life-table construction and analysis in the evaluation of natural enemies. Annu Rev Entomol 37:587–612

Bergmann EJ, Venugopal PD, Martinson HM et al (2016) Host plant use by the Invasive *Halyomorpha halys* (Stål) on woody ornamental trees and shrubs. PLoS ONE 11:e0149975. doi:10.1371/journal.pone.0149975

Callot H, Brua C (2013) *Halyomorpha halys* (Stal, 1855), la punaise diabolique, nouvelle espece pour la faune de France (Heteroptera Pentatomidae). L'Entomologiste, pp 69–71

Cesari M, Maistrello L, Ganzerli F et al (2015) A pest alien invasion in progress: potential pathways of origin of the brown marmorated stink bug *Halyomorpha halys* populations in Italy. J Pest Sci 88:1–7. doi:10.1007/s10340-014-0634-y

Dioli P, Leo P, Maistrello L (2016) Prime segnalazioni in Spagna e in Sardegna della specie aliena *Halyomorpha halys* (Stål, 1855) e note sulla sua distribuzione in Europa (Hemiptera, Pentatomidae). Rev Gaditana Entomol 7:539–548

EUROSTAT (2017) The fruit and vegetable sector in the EU—a statistical overview—Statistics Explained. http://ec.europa.eu/eurostat/statistics-explained/index.php/The_fruit_and_vegetable_sector_in_the_EU_-_a_statistical_overview#Fruit:_holdings.2C_areas_and_production. Accessed 15 Jan 2017

Fanfani R, Pieri R (2016) Il sistema agro-alimentare dell'Emilia-Romagna. Rapporto 2015. Unione regionale delle Camere di commercio dell'Emilia-Romagna Regione Emilia-Romagna, Assessorato agricoltura, caccia e pesca, Bologna

Funayama K (2012) Nutritional states of post-overwintering adults of the brown-marmorated stink bug, *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae). Jpn J Appl Entomol Zool 56:12–15

Gariepy TD, Haye T, Fraser H, Zhang J (2014) Occurrence, genetic diversity, and potential pathways of entry of *Halyomorpha halys* in newly invaded areas of Canada and Switzerland. J Pest Sci 87:17–28. doi:10.1007/s10340-013-0529-3

Haye T, Abdallah S, Gariepy T, Wyniger D (2014) Phenology, life table analysis and temperature requirements of the invasive brown marmorated stink bug, *Halyomorpha halys*, in Europe. J Pest Sci 87:407–418

Haye T, Gariepy T, Hoelmer K et al (2015) Range expansion of the invasive brown marmorated stinkbug, *Halyomorpha halys*: an increasing threat to field, fruit and vegetable crops worldwide. J Pest Sci 88:665–673. doi:10.1007/s10340-015-0670-2

Heckmann R (2012) Erster nachweis von *Halyomorpha halys* (Stål, 1855) (Heteroptera: Pentatomidae) für Deutschland. Heteropteron Heft 36:17–18

Hoebeke ER, Carter ME (2003) *Halyomorpha halys* (Stål) (Heteroptera: Pentatomidae): a polyphagous plant pest from Asia newly detected in North America. Proc Entomol Soc Wash 105:225–237

Inkley DB (2012) Characteristics of home invasion by the brown marmorated stink bug (Hemiptera: Pentatomidae). J Entomol Sci 47:125–130. doi:10.18474/0749-8004-47.2.125

Kawada H, Kitamura C (1983) The reproductive behavior of the brown marmorated stink bug, *Halyomorpha mista* Uhler (Heteroptera, Pentatomidae). 1. Observation of mating-behavior and multiple copulation. Appl Entomol Zool 18:234–242

Koch RL, Rich WA (2015) Stink bug (Hemiptera: Heteroptera: Pentatomidae) feeding and phenology on early-maturing soybean in Minnesota. J Econ Entomol 108:2335–2343. doi:10.1093/jee/tov218

Lee D-H, Leskey TC (2015) Flight behavior of foraging and overwintering brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). Bull Entomol Res, pp 1–8. doi: 10.1017/S0007485315000462

Lee D-H, Short BD, Joseph SV et al (2013) Review of the biology, ecology, and management of *Halyomorpha halys* (Hemiptera: Pentatomidae) in China, Japan, and the Republic of Korea. Environ Entomol 42:627–641. doi:10.1603/EN13006

Leskey TC, Hamilton GC, Nielsen AL et al (2012a) Pest status of the brown marmorated stink bug, *Halyomorpha halys* in the USA. Outlooks Pest Manag 23:218–226. doi:10.1564/23oct07

Leskey TC, Short BD, Butler BR, Wright SE (2012b) Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in mid-Atlantic tree fruit orchards in the United States: case studies of commercial management. Psyche J Entomol 2012:1–14. doi:10.1155/2012/535062

Leskey TC, Wright SE, Short BD, Khrimian A (2012c) Development of behaviorally-based monitoring tools for the brown marmorated stink bug (Heteroptera: Pentatomidae) in commercial tree fruit orchards. J Entomol Sci 47:76–85. doi:10.18474/0749-8004-47.1.76

Macavei L, Băeţan R, Oltean I et al (2015) First detection of *Halyomorpha halys*, a new invasive species with a high potential of damage on agricultural crops in Romania. Lucr Stiintifice Ser Agron 58:105–108

Maistrello L, Costi E, Caruso S et al (2016a) *Halyomorpha halys* in Italy: first results of field monitoring in fruit orchards. IOBC-WPRS Bull 112:1–5

Maistrello L, Dioli P, Bariselli M et al (2016b) Citizen science and early detection of invasive species: phenology of first occurrences of *Halyomorpha halys* in Southern Europe. Biol Invasion 18:3109–3116. doi:10.1007/s10530-016-1217-z

Maistrello L, Vaccari G, Caruso S et al (2017) Monitoring of the invasive *Halyomorpha halys*, a new key pest of fruit orchards in northern Italy. J Pest Sci. doi:10.1007/s10340-017-0896-2

Maurel J-P, Blaye G, Valladares L et al (2016) *Halyomorpha halys* (Stal, 1855), la punaise diabolique en France, ā Toulouse (Heteroptera; Pentatomidae). Carnets Nat 3:21–25

Medal J, Smith T, Fox A et al (2012) Rearing the brown marmorated stink bug *Halyomorpha halys* (Heteroptera: Pentatomidae). Fla Entomol 95:800–802

Milonas PG, Partsinevelos GK (2014) First report of brown marmorated stink bug *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) in Greece. EPPO Bull 44:183–186. doi:10.1111/epp.12129

Mityushev IM (2016) First record of marmorated bug detection in Russia. Zashchita Karantin Rasteniĭ 3:48

Nielsen AL, Hamilton GC, Matadha D (2008) Developmental rate estimation and life table analysis for *Halyomorpha halys* (Hemiptera: Pentatomidae). Environ Entomol 37:348–355

Niva CC, Takeda M (2003) Effects of photoperiod, temperature and melatonin on nymphal development, polyphenism and reproduction in *Halyomorpha halys* (Heteroptera: Pentatomidae). Zool Sci 20:963–970. doi:10.2108/zsj.20.963

Philips CR, Kuhar TP, Dively GP et al (2016) Seasonal abundance and phenology of Halyomorpha halys (Hemiptera: Pentatomidae) on different pepper cultivars in the Mid-Atlantic (United States). J Econ Entomol 110:192–200. doi:10.1093/jee/tow256

Rabitsch W, Friebe GJ (2015) From the west and from the east? First records of *Halyomorpha halys* (Stål, 1855)(Hemiptera: Heteroptera: Pentatomidae) in Vorarlberg and Vienna. Beitr Entomof 16:115–139

Rice KB, Bergh JC, Bergmann EJ et al (2014) Biology, ecology, and management of brown marmorated stink bug (Hemiptera: Pentatomidae). J Integr Pest Manag. 5(3):A1–A13. doi:10.1603/IPM14002

Šeat J (2015) *Halyomorpha halys* (Stål, 1855) (Heteroptera: Pentatomidae) a new invasive species in Serbia. Acta Entomol Serbica 20:167–171

Simberloff D, Martin J-L, Genovesi P et al (2013) Impacts of biological invasions: what's what and the way forward. Trends Ecol Evol 28:58–66. doi:10.1016/j.tree.2012.07.013

Simov N (2016) The invasive brown marmorated stink bug Halyomorpha halys (Stål 1855 (Heteroptera: Pentatomidae) already in Bulgaria. Ecol Montenegrina 9:51–53

United States Apple Association (2010) Asian pest inflicting substantial losses, raising alarm in eastern apple orchards. Apple News 41:488

USDA-NIFA SCRI (2017) Stop BMSB. Biology, ecology, and management of brown marmorated stink bug in specialty crop. In: Stop BMSB. http://www.stopbmsb.org. Accessed 20 Jan 2017

Van Driesche R, Hoddle M, Center T (2008) Control of pests and weeds by natural enemies: an introduction to biological control. Blackwell Publishing, Oxford

Venugopal PD, Dively GP, Lamp WO (2015) Spatiotemporal dynamics of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) in and between adjacent corn and soybean fields. J Econ Entomol 108:2231–2241. doi:10.1093/jee/tov188

Vetek G, Papp V, Haltrich A, Redei D (2014) First record of the brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Heteroptera: Pentatomidae), in Hungary, with description of the genitalia of both sexes. Zootaxa 3780:194–200

Wang Y, Wang Y (1988) Studies on the pear bug, *Halyomorpha picus*. Acta Agric Bor-Sin 3:96–101

Watanabe M (1980) Study of the life cycle of the brown marmorated stink bug, *Halyomorpha mista* by observing ovary development. Insectarium 17:168–173

Wermelinger B, Wyniger D, Forster B (2008) First records of an invasive bug in Europe: *Halyomorpha halys* Stal (Heteroptera: Pentatomidae), a new pest on woody ornamentals and fruit trees? Mitt Schweiz Entomol Ges 81:1–8

Wiman NG, Walton VM, Shearer PW et al (2014) Factors affecting flight capacity of brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae). J Pest Sci. doi:10.1007/s10340-014-0582-6

Xu J, Fonseca DM, Hamilton GC et al (2014) Tracing the origin of US brown marmorated stink bugs, *Halyomorpha halys*. Biol Invasion 16:153–166. doi:10.1007/s10530-013-0510-3

Yanagi T, Hagihara Y (1980) Ecology of the brown marmorated stink bug. Plant Prot 34:315–321

Zhang CT, Li D, Su H, Xu G (1993) A study on the biological characteristics of *Halyomorpha picus* and *Erthesina fullo*. For Res China 6:271–275

Zhu G, Gariepy TD, Haye T, Bu W (2016) Patterns of niche filling and expansion across the invaded ranges of *Halyomorpha halys* in North America and Europe. J Pest Sci. doi:10.1007/s10340-016-0786-z