New insights into the life history of *Monochamus saltuarius* (Cerambycidae: Coleoptera) can enhance surveillance strategies for pine wilt disease

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Abstract Pine wilt disease was first discovered in Dongtang town, Liaoning Province, China, in 2017. *Monochamus saltuarius* Gebler is a new vector of pinewood nematode and the only known vector in Liaoning Province. The biology of this pest has not been reported thus far; therefore, it is necessary to study its life history. During 2018 and 2019, we collected 138 and 491 adult *M. saltuarius* beetles, respectively, to analyze their eclosion from larva to adult stage. In mid-March, overwintering larvae began to feed (on xylem) and seek nutrition in preparation for pupation and eclosion. The adults began to appear in mid-April, and the population reached its peak in late May. The life span of the adults was 28–76 days. After approximately 1 week of supplemental nutrition (feeding on twigs), adults began to mate and lay eggs. The egg stage of *M. saltuarius* lasted 4–8 days. The larvae in Dongtang town have 4 instars and overwinter in tunnels as 3rd–4th instars. The 1st-instar stage lasted 3–9 days, the 2nd-instar stage lasted 11–23 days, the 3rd-instar stage lasted 30–130 days, and the 4th-instar stage

lasted 44–180 days. The pupal stage lasted 7–12 days, and the life span of the adults was 28–76 days. In this study we systematically monitored the life history of *M. saltuarius* for the first time. Our objective was to lay a foundation for improving control of this pinewood nematode vector.

Keywords *Bursaphelenchus xylophilus* · China · Pine sawyer · Life cycle · Vector

Introduction

Pine wilt disease is caused by pinewood nematode, *Bursaphelenchus xylophilus* (Steiner and Buhner 1934), and represents one of the most serious global threats to conifer trees. The pinewood nematode, an invasive species native to North America, survives and successfully reproduces in East Asian conifer trees (Togashi and Jikumaru 2007). The pinewood nematode was accidentally introduced into Japan (Mamiya 1988) in the early twentieth century and subsequently introduced into China (Sun 1982), Korea (Han et al. 2008) and other countries (Rodrigues 2009), where it has caused massive local mortality of conifers (Foit et al. 2019). In 1982, pine wilt disease was first identified in *Pinus thunbergii* Parl. in Nanjing city, Jiangsu Province where 256 dead trees were recorded within an area of 200 ha. Although this initial outbreak was fully controlled, the total loss of pine trees caused by pine wilt disease in China in recent decades has led to economic losses reaching hundreds of billions of Chinese yuan, and the disease is still expanding rapidly in China (Zhang 2010). In 2016 and 2017, pine wilt disease spread for the first time to Shahekou city, Dalian, and Fengcheng city, Dandong, Liaoning Province, both in northeast China, and caused pine tree deaths over large areas.

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Similar to other disease-causing nematodes, the pinewood nematode requires an insect vector to be transported from one tree to another, and the vectors are cerambycid beetles in the genus *Monochamus* (Aikawa 2008). To date, 13 species of *Monochamus* beetles have been shown to transmit pinewood nematode. In North America, *M. carolinensis* Olivier (Linit 1990), *M. scutellatus* Say (Holdeman 1980), *M. titillator* Fabricius (Luzzi et al. 1984), *M. obtusus* Casey (Akbulut and Stamps 2012), *M. notatus* Drury, *M. marmorator* Kirby and *M. mutator* LeConte (Wingfield and Blanchette 1983) are vectors of *B. xylophilus*. In Asia, *M. alternatus* Hope (Mamiya and Enda 1972), *M. saltuarius* (Sato et al. 1987) and *M. nitens* Bates (Harman 1985) can transport *B. xylophilus*. *M. sutor* Linnéand (Pajares et al. 2017) and *M. urusovi* Fischer-Waldheim (Togashi et al. 2008) have been identified as vectors of pinewood nematode throughout Europe. *Monochamus galloprovincialis* Olivier (Akbulut et al. 2008; Pajares et al. 2010) was identified in Europe and North Africa and has been reported to be responsible for local pinewood nematode transmission.

Before *M. saltuarius* was identified as a new pinewood nematode vector in China, it was known as a common pine forest pest in Liaoning, Jilin and Heilongjiang provinces that had not attracted much attention in these areas. In fact, *M. saltuarius* has long been recognized as one of the transmission vectors of the pinewood nematode in Japan (Jikumaru and Togashi 1995), South Korea (Kim et al. 2006) and other East Asian regions. In these regions, pinewood nematode has caused mass mortality of native pine species, considerable economic and environmental damage, and substantial annual losses of timber (Zhao et al. 2008). In Dandong, native conifer trees, such as *Pinus koraiensis* Sieb., *Pinus armandii* Franch., and *Larix gmelinii* Rupr., have suffered severe damage due to pine wilt disease carried by *M. saltuarius* infected with the pinewood nematode. In other areas where pine wilt disease has not yet spread, the presence of vector insects must know for the risks of extension and possible damage to be properly assessed. Pest monitoring will identify where a pest is found and help to quantify its rate of movement into an area (Augustin et al. 2012). Every year, the General Station of Forest Pest Management surveys the national forest areas in China, to address areas that have been classified as epidemic areas, and to strengthen the protection and monitoring of the areas around the epidemic areas (Li and Yao 2019).

The life cycle of *M. alternatus* has been studied thoroughly worldwide. The behavior of adults, egg laying and larva development of *M. alternatus* were studied in detail using cages with twigs and pieces of logs (Zhou and Togashi 2006). However, little is known about its life cycle and biology in China. Because *M. alternatus* appeared only recently as a new vector of the Pinewood nematode in China, its biology and other characteristics are yet to be fully described.

Although pine wilt disease is currently present in only Liaoning Province among several provinces in northeast China, the consequences of beetles vectoring the pinewood nematode into other provinces are unknown. Monitoring the vectors of pinewood nematode has become a key strategy for the monitoring of pine wilt disease in China. Many trap designs have been developed to capture vectors of the pinewood nematode for population monitoring or for large-scale trapping of *Monochamus* spp. (Xu et al. 2018).

Pine wilt disease might continue to spread to regions with a relatively cold climate and cause mortality in native pine species despite preventive efforts by government agencies. Therefore, detailed understanding of the biology of *M. saltuarius* is needed for the development of pest management strategies that can prevent the dissemination of the pinewood nematode and control pine wilt disease by efficiently controlling its vector. We studied the life history of *M. saltuarius* with the aim of providing a reliable reference for the prevention and control of pests and pinewood nematodes.

Materials and methods

Study area

Our study area was located in the pine wilt disease epidemic area of Dongtang town (Fig. 1). Five separate sites were selected for field trapping experiments. The five locations

Fig. 1 Locations of the test sites in Dongtang town. 1. Xiaolingziling (E118° 15' 46", N40° 26' 58"), 2. Beishantou (E118° 16' 58", N40° 26' 30"), 3. Qiangwai (E118° 17' 12", N40° 26' 26"), 4. Zhuangaizi (E118° 17' 42", N40° 25' 17"), and 5. Tangling (E118° 17' 43", N40° 24' 14")

were Xiaolingziling (E118° 15' 46", N40° 26' 58"), Beishantou (E118° 16' 58", N40° 26' 30"), Qiangwai (E118° 17' 12", N40° 26' 26"), Zhuangaizi (E118° 17' 42", N40° 25' 17") and Tangling (E118° 17' 43", N40° 24' 14"); the minimum distance between sites was approximately 1200 m. Dongtang town has a mean annual temperature of 3.3 °C (data provided by the Dandong Meteorological Bureau), mean annual rainfall of 900–1000 mm, and mean relative humidity of 63%. The area is rich in soil and pine forest resources, and the predominant tree species are *P. koraiensis*, *P. armandii*, *Pinus tabulaeformis* Carr. and *L. gmelinii*, all of which are reported to be susceptible to pine wilt disease (Han et al. 2008; Nakamura et al. 2010; Shi et al. 2012; Yu et al. 2019).

Adult eclosion rules

We studied the acquisition of flight dynamics of adult *M. saltuarius* by capturing the beetles in Dongtang town over a two-year period from 2018 to 2019. Beetles were captured in improved commercial traps (F2 attractant traps supplied by Hangzhou Felomon Biotechnology Co., Ltd. China) (Zhang et al. 2018). The attractant core consisted of two components. The first component was a blend of alpha- and beta-pinene in a plastic bottle, and the second component was the aggregation pheromone 2-undecyloxy-1-ethanol dispensed as flakes. Both components provided a release rate of 2.7 µg/day at 25 °C. The trap consisted of a top cover, a cross baffle, a trap, a funnel and a collection bottle (Fig. 2a). Twenty-five F2 attractant traps were hung approximately 3 m from the ground, with 30 m spacing between traps (Chen et al. 2014), and five traps were installed at each of the five sites in the pine wilt disease epidemic area of Dongtang town. The trees at each site were located in 50- to 60-year-old pure Korean pine forests. From the beginning of April to the beginning of September in 2018 and 2019, we checked traps and removed beetles for identification every 2 days in accordance with an established method for capturing adult *Monochamus* in pine

forests (Pimentel et al. 2014). Traps were easy to deploy and monitor, making it feasible to sample geographically distant locations.

Adult mating and oviposition

Captured adult beetles were kept in covered field cages (2 m × 2.5 m × 2 m) with sidewalls made of 0.2-cm metal mesh. Newly cut wood was placed in the cages for the adults to lay eggs on, and the cut ends of the wood were sealed with paraffin to prevent water loss. Fresh *P. koraiensis* twigs were also placed in the cages for adult feeding. Every 7 days, the wood pieces supplied for oviposition were removed from the adult cages and placed in new cages to record the time to eclosion (Fig. 2b).

Larval development

The first wood piece with eggs was placed in a cage on July 6, 2018. At the beginning of the experiment, it was necessary to observe egg hatching for several days, and 10 egg-laying slits were checked every day to inspect egg status. As the larvae developed, the observation schedule was modified to once every 15 days. The methods for observing insect stage and age were described by Wang (Wang 2002). Observations were performed in the egg-laying slits under the bark, in the phloem, and finally in the sapwood until the larvae were located. The tunnel in the log caused by larval feeding was checked to determine the exact position of the larvae in the log. Larvae with a milky white body color and feces in the intestine were considered to be feeding, while those with empty intestines and of yellowish white to yellow color were considered to be in diapause. Monitoring was stopped in November (the larvae did not develop during the cold season) and started again in March of the following year until eclosion. The stage of each instar and the head width of the larvae were recorded from 2018 to 2019.

Fig. 2 Trap suspension apparatus and net field cages. Suspension mode of the F2 attractant trap (a). Net cages containing logs for oviposition (b)

Trap sample examination

Captured beetles were sent to Fengcheng Forestry Pest Control Laboratory for identification and classification. If an insect could not be sent to the laboratory immediately, it was placed in a freezer at 4 °C until the next sample delivery. Over two years of field trapping experiments, 1290 insects were collected (non-coleopteran insects were not counted in 2018), and among these insects, 16% could not be identified to species (mainly weevils and Scolytidae). Captured *M. saltuarius* were examined in detail and sexed.

Results

Dynamics of adult *M. saltuarius* occurrence

In 2018 and 2019, field trapping of adult *M. saltuarius* began on April 1 and ended on August 31. According to the results of two years of investigation, one *M. saltuarius* generation was produced every year in Dongtang town (Figs. 3, 4). Adult *M. saltuarius* flying dynamics peaked in late May. During this period, 39 adults eclosed in 2018, and 232 adults eclosed in 2019, accounting for 28% and 24% of the total adults in 2018 and 2019. Among these adults, the flying dynamics peak in 2018 and 2019 occurred on May 27 and May 24, with 21 and 84 adult flying events, respectively. Subsequently, the number of adult flying events decreased significantly. Beginning on June 26, 2018, and July 5, 2019, *M. saltuarius* adult flying decreased gradually. After July 21, 2018, essentially no *M. saltuarius* eclosed. In 2018 and

Fig. 4 Eclosion period of adult *Monochamus saltuarius* in Dongtang town

2019, the adult trapped of *M. saltuarius* were generally the same, as were the dates of peak occurrence.

In 2018, 138 adults were trapped in the pine wilt disease epidemic area in Dongtang town, with a mean of 2.76 beetles per trap; the ratio of females to males was 2.14:1. The number of adults captured in 2019 was significantly higher than in 2018. A total of 491 adults were trapped in the epidemic area, with a mean of 9.82 beetles per trap; the ratio of females to males was 1.15:1 (Table 1).

Mating and oviposition behaviors in *M. saltuarius* adults

Before mating, male and female adults required several to dozens of minutes for mutual adaptation. The mating times of each pair of adults differed after one mating. Some of the pairs separated immediately after mating, while others mated repeatedly. After one mating event, male and female adults could copulate with the same partner or copulate with a different partner. Thus, there was no individual specificity between males and females. Mating occurred between one male and multiple females and also between one female and multiple males. Some male and female adults copulated at

Fig. 3 Adults of *Monochamus saltuarius*. Female adult (a), male adult (b). Bar = 5 mm

Table 1 Number of *Monochamus saltuarius* trapped in 2018 and 2019

Year	Total adult beetles	Female adult beetles	Male adult beetles
2018	138	94	44
2019	491	263	228

different times, and some copulated 4 times consecutively, usually for 1–2 min each time. Female adults copulated while feeding, and both males and females were provided supplemental nutrition after copulation. Before laying eggs, the females excavate slits into the tree trunk and then insert their ovipositor into the slit to lay eggs.

M. saltuarius adult life span

New twigs were provided every 3 days to provide continuous supplemental nutrition for the adults in the cages. Daily observations revealed that the life spans of female and male adults were ranged from 28–76 to 37–69 days, respectively. Beetles lived only 5–16 days without feeding.

Larval development

In Dongtang town, two years are required for *M. saltuarius* to complete its life cycle (Table 2, Fig. 5). Old-instar larvae mainly survived through the winter in the xylem, and

a few lived through the winter in the phloem. In the middle of March of the following year, the overwintering larvae began to move and continued to feed. In the first 10 days of April, the larvae began to eat, and pupation and adult eclosion began in mid-April. In the first 10 days of May, there were egg-laying slits (Fig. 5a) in the wood. Females began to oviposit and larvae appeared in mid-May. July and August were the peak periods for egg hatching. The larvae successively overwintered starting in late October or early November. Due to differences in climatic and forest conditions, the time of adult eclosion differed among the areas. The time of adults eclosion is very important for nematode spread because transmission occurs by the adult through feeding, swarming and breeding. The earliest eclosion of adults occurred within the first 10 days of April. Therefore, trap monitoring should start within the first 10 days of March.

Table 2 Life cycle of *M. saltuarius* in Dongtang town

January–March	April	May	June	July	August	September	October–December
(▲▲▲)	▲▲▲ ■ ■ ■ ★ ★	▲▲▲ ■ ■ ■ ★ ★ ★ ● ● ●	▲▲▲ ■ ■ ■ ★ ★ ★ ● ● ●	▲ ▲ ■ ■ ■ ★ ★ ★ ● ● ●	■ ★ ★ ● ● ●	▲ ▲ ▲	(▲▲▲)

▲ represents larval stage, (▲) represents overwintering larvae, ■ represents pupal stage, ★ represents adult stage, and ● represents egg stage. Three symbols indicate the first, middle and last days of the month

Fig. 5 *Monochamus saltuarius* development process. Egg-laying slit (a), egg under the egg-laying slit (b), 1st-instar larva (c), 2nd-instar larva (d), 3rd-instar larva (e), 4th-instar larva (f), pupa (g), and entry and eclosion holes (h). Bar=2 mm

Eggs

The eggs (Fig. 5a) of *M. saltuarius* were long and oval, approximately 0.43 cm in diameter, slightly concave in the middle, and uneven in size at the ends. The eggs were generally laid in the lowest part of the egg laying slit, with the small side facing down. When the bark was cut open, the outer layer of the egg cuticle was surrounded by turpentine. The egg casing had two layers: the outer layer was thick and light yellow and had a mesh-like structure that prevented the eggs from hatching due to soaking in turpentine. The inner layer was thin and had a white membrane with no such structure. The egg laying period occurred from the first 10 days of May to the last 10 days of August, and the peak egg laying period was from June to July. The duration of the egg stage typically ranged from 4 to 8 days, with the longest duration being 12 days.

Larvae

In Dongtang town, most larvae started to hatch in mid-May. June to July was the peak period for egg hatching. Of the 304 eggs observed by dissection, 23 were dry and black in appearance. These eggs might have been infected by fungi (Alvarez et al. 2015) or were unfertilized (Zhang and Linit 1998). No natural enemies, such as parasitoids, were found. The egg hatching rate reached 92%. When hatching, the larva used its upper jaw to bread the casing along the long axis of the egg and then exited the egg casing. After hatching, the larva did not eat the egg casing but, rather, fed on pine bark.

Larval *M. saltuarius* developed through 4 instars, with the larval stage lasting 245–332 days. Head width values for each age range are shown in Fig. 6 and Table 3.

The newly hatched larvae (Fig. 5b) were white and approximately the same length as the egg casing. They first ate the phloem of the endodermis in pine trees. Brown matter could be seen in the digestive tract, and brown powdery excrement was found at the feeding mark of the endodermis. The 2nd-instar larvae (Fig. 5c) gradually fed on the surface of the sapwood, forming a curved, shallow and irregular borehole. The borehole was filled with brown powder, white borehole fibers and frass. At this time, brown and white boreholes could be seen outside the bark; these marks were an early indicator of damage caused by *M. saltuarius*. The larvae grew for 15–30 days in the cortex and sapwood. The 3rd- (Fig. 5d) and 4th-instar (Fig. 5e) larvae began to bore into the xylem. Oblate and circular boreholes (Fig. 5g) of 0.5–1.1 cm length and 0.2–0.5 cm diameter were observed in the xylem. When larvae passed through the phloem to the xylem, they generally approached from the sapwood to the center, and no vertical borehole was found. The larvae fed in an upward or downward direction after entering the section

Fig. 6 Frequency distribution of head capsule width for 320 larvae of *Monochamus saltuarius* from 2018 to 2019

horizontally. The length of the borehole was related to the size of the larva. The length of a large borehole containing a mature larva reached 10.3 cm, while short boreholes were 6.5 cm. The larva usually accumulated feces and bores under the bark, and the larvae present in the xylem expelled sawdust and feces outward. A large amount of sawdust accumulated under the bark near the mouth of the hole, forming a dense layer. After larval entry into the xylem, no sawdust or feces was seen outside the bark.

Beetles overwintered from October to March, during which time the larvae ceased their activity and almost completely stopped eating. Most of the 3rd–4th instar larvae overwintered in the bored tunnel, and a few of the 2nd–3rd instar larvae overwintered under the bark, mostly in the thick bark at the base of the trunk. The chambers of the mature larvae in the xylem were constructed before overwintering and were clean, without sawdust or feces.

After overwintering, the larvae continued to eat and then formed a pupal chamber, in which the mature larvae pupated. The length and diameter of the pupal chamber were both approximately 3.63 cm. The short diameter was 1.54 cm. Some larvae pupated under the bark. When the larvae pupated, they formed a circular tunnel that was deeper than the borehole. At first, the pupa (Fig. 5f) was completely milky white. After 4–5 days, the pupa turned slightly yellow, and the compound eyes turned a light brown color. On the 6th day, the maxilla started to turn light reddish brown and finally turned brown or blackish brown. Similar to the compound eyes, on the 7th day, the ends of the claws, appendages of the foot, and ends of the tibia and legs became light brown. On the 9th day, the elytra turned gray or grayish black, and on the 10th day, the legs and antennae, which were movable, began to unfold, but the wings were not hard.

Table 3 Larval duration and head width of *M. saltuarius* in Dongtang town

Instar	Duration (days)	Mean (days)	Head width (cm)	Mean (cm)
Eggs	4–8	4	–	–
1st-instar larvae	3–9	6.8	0.083–0.138	0.121
2nd-instar larvae	11–23	15.8	0.139–0.194	0.172
3rd-instar larvae	30–130	68.3	0.204–0.268	0.245
4th-instar larvae	44–180	91.6	0.271–0.332	0.301
Pupa	7–12	9.5	0.333–0.421	0.369

On the 11th–12th day, the elytra began to harden, and the beetles finally completed their eclosion.

Discussion

Although *M. saltuarius* is found in many parts of the world, this species' life history has not attracted much attention or research interest as a pest, probably because *M. alternatus* is present in the same areas. *M. alternatus*, by comparison, has caused environmental and economic losses and this insect is an efficient vector of pine wilt disease (Akbulut and Stamps 2012). In recent years, scholars have paid particular attention to the mating mode and other related aspects of *M. saltuarius* (Kobayashi et al. 2003; Anbutsu and Togashi 2008). *M. saltuarius* is a new vector of the pinewood nematode in China. Based on the biological characteristics and life cycle of *M. saltuarius*, it is necessary to formulate scientific control measures and determine appropriate control periods. At present, experiments are being carried out only in Dongtang town. The life cycle of *M. saltuarius* in other areas of China needs to be further studied. The number of larval stages in *M. saltuarius* had not been confirmation. Our results clearly show that there are four stages, and we determined their size characteristics. With regard to the age classes of *M. saltuarius*, many scholars consider that beetles of the genus *Monochamus* have 5 age classes (Naves et al. 2006; Liu et al. 2008), but Koutroumpa (Koutroumpa et al. 2008) and Togashi (Togashi 1990) found that *M. galloprovincialis* and *M. alternatus* have four larval instars. According to the age classification method recommended by these previous authors, only four age classes were observed in *M. saltuarius*. There are many reason for this difference; one possible reason is that summer in Dongtang town is short and *M. saltuarius* begin to overwinter in October, at which point its development is suspended. In March, the weather gradually warms, and the insects start to move and eat. Due to the long dormancy period of beetles in this area, there is no significant difference between the 4th-instar larvae and 5th-instar larvae.

The number of beetles collected in the second year was approximately 3.5 times that collected in the first year. The ratio of males to females was 2.41:1 in 2018 but gradually

returned to 1.15:1 in 2019. The increased proportion of female beetles in 2018 may be a response by *M. saltuarius* to excessive disruption of the local population by humans (Peer and Taborsky 2004). The entrapment records for 2019 show that the number actually increased greatly compared with that in the previous year. Because *M. saltuarius*, similar to other beetles, may adjust the sex ratio of its offspring according to the environment and population, it is even more important to strengthen efforts to protect pine trees from pine wilt disease. *M. saltuarius* larvae conceal themselves by boring holes into and feeding on pine tree tissues, making control by chemical agents very difficult at this stage. The thorough cleaning of dead wood harboring a large number of *M. saltuarius* larvae before adult eclosion can significantly reduce the population density of this forest pest and is an effective measure for preventing and controlling this pest (Kwon et al. 2011). However, pine trees have a lag period between initial infestation and display of wilt symptoms; thus, visually healthy but infected trees could be a source of infection for a given period. At present, cleaning of dead wood generally occurs from December to January of the next year, but at that time, visually healthy but infected trees are likely to be ignored. Some of these trees can be distinguished by observing whether the trunk has the egg-laying slits or not, but the slit is too small to be found with high probability.

Monochamus saltuarius is exposed in only the adult stage, and this stage serves as a vector of the pinewood nematode. The pinewood nematode can be spread by the movement of *M. saltuarius*. Reducing the density of adults in the forest in a timely manner is the key to controlling pine wilt disease. The duration before adult eclosion is long, and there are many rainy days during the peak active period in May, making it difficult to effectively use traditional chemical control methods. Due to the long-term use of chemical pesticides, some pests have developed strong pesticide resistance, and many natural enemies of pests have been killed in large quantities, leading to explosive population growth in some pests. Biological control can effectively overcome the above shortcomings and thus has broad application potential. The most environmentally friendly form of biological control of diseases and insect pests is the use of natural enemies or microorganisms,

predatory birds or other measures. Through experiments, Cheng showed that *Scleroderma guani* is a natural parasitic enemy of the larvae and pupae of Cerambycidae and can aid natural control of wood borers (Cheng et al. 2003). Yan et al. (2014) found that the mortality rate of *Monochamus* beetles was as high as 64.6% in a control experiment with *Dastarcus helophoroides*, and the effect was significant.

Before the occurrence of pine wilt disease in Liaoning Province, it was thought that the pinewood nematode could not survive in this area of China because of its annual mean temperature of 10 °C (Quan et al. 2005). However, some isolates of pinewood nematodes have evolved since they invaded Liaoning Province, becoming more virulent and better adapted to low temperatures than the pinewood nematode found in the warm areas of South China. *M. saltuarius*, which originated from high latitudes, has adapted to low temperatures. Therefore, it is very important to develop a deep understanding of *M. saltuarius* ecology in cold climates.

Conclusion

The larvae of *M. saltuarius* in Dongtang town, Liaoning Province, developed through 4 instars and overwintered in the borehole with 3–4 instars. The egg stage was 4–8 days, the 1st-instar larval stage was 3–9 days, the 2nd-instar larval stage was 11–23 days, the 3rd-instar larval stage was 30–130 days, the 4th-instar larval stage was 44–180 days and the pupal stage was 7–12 days. Adults began to appear in the middle of April, and the population size peaked in late May. After approximately 1 week of supplementary nutrition, the adults began to mate and lay eggs. The life span of the adults was 28–76 days. The study of the pine sawyer *M. saltuarius* as a vector of the pine wilt nematode will provide fundamental data to establish effective prevention measures for addressing this devastating disease.

Authors' contribution LM and CFM conceived and designed the research. LM conducted the experiments. SSH contributed new reagents. DY, WY and WLC analyzed the data. LM wrote the manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest. This article does not contain any experiments with human participants or animals performed by any of the authors.

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