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Cyclic Behavior of *Lycorma delicatula* (Insecta: Hemiptera: Fulgoridae) on Host Plants

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Abstract *Lycorma delicatula* is an invasive insect species in Korea, and its populations are increasing. It sucks plant sap and can cause withering of the whole trees. To prevent damage to fruit trees, it is important to determine the behavioral characteristics of *L. delicatula*. We monitored migration patterns and host plant preferences, from the egg mass on the tree bark, through egg hatching to egg laying. Most eggs hatched between 0500h and 0800h. The nymphs ascended trees until they reached the leaves. They often fell to the ground because of physical factors, such as wind, but then ascended the trees again on the upper sides of the branches. Their falling-ascending cycle became longer as their arolia developed. The host preference changed over the course of its growth, from a broad range of plant species at the early nymph stage to a few plant species, such as *Ailanthus altissima* at the adult stage. We summarize the life cycle behavior as follows. Initially, there is a short-term cycle of falling and ascending, which becomes longer as the nymphs age. The other cycle is a yearly cycle of host plant preferences, with broad host preference in the early nymph stage and a narrower host preference in the adult stage. Knowledge of this cyclic behavior can be used to prevent the rapid expansion of *L. delicatula* populations in orchards.

Key words: *Ailanthus altissima,* falling-ascending cyclic behavior, host plant preference, insect control, invasive species, *Lycorma delicatula*

Introduction

Lycorma delicatula White, 1845 (Hemiptera: Auchenorrhyncha: Fulgoridae: Aphaeninae: Fulgorid hopper) is an invasive insect species in Korea that originated from the southern part of China and other subtropical regions of Southeast Asia (Xiao 1992). *Lycorma delicatula* has a univoltine and survives the winter as eggs in an ootheca. These eggs hatch in mid-May, and emergent nymphs then start sucking sap from trees (Park et al. 2009). Both nymphs and adults of *L. delicatula* suck sap from the vascular bundles of young stems or leaves (Ding et al. 2006). They excrete large quantities of fluid, which cover the stems or leaves of trees. This excretion hastens the growth of mold, which weakens the plant and can eventually kill it (Li and Tao 1980). *Lycorma delicatula* also uses grape vines as a host plant, thereby damaging them (Park et al. 2009).

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In Korea, *Lycorma sp.* was first recorded by Doi in 1932, but there is no record of this species in Korea until 2006. Because of cold intolerance, *L. delicatula* of the egg stage presumably failed to hibernate in Korea. However, winter temperatures have increased since 2006, resulting in survival of *L. delicatula* eggs and dramatic increases in populations of this pest (Park et al. 2009). *Lycorma delicatula* was first reported in Seoul in the middle of the Korean peninsula in 2006 and has since spread to the western parts of Korea such as Go-yang, In-cheon, Won-ju, Chung-ju, and Cheon-an (Han et al. 2008), as well as southern regions, such as Sang-ju and Busan (Park et al. 2009). Thirty-eight species of trees and three species of herbs are known to be host plants of *L. delicatula* in Korea, indicating prefererence of *Juglans mandshurica*, *Cedrela fillilis*, *Toona sinensis*, *Evodia danielii*, *Phellodendron amurense*, *Picrasma quassioides*, *Ailanthus altissima* (tree-of-heaven), *Parthenocissus quinquefolia*, *Vitis amurensis*, and *V. vinifera* (Park et al. 2009). With the exceptions of *A. altissima* and *Vitis spp.*, these hosts are not common in Korea. However, the density of *Vitis* spp. is high because these plants are cultivated. The density of *A. altissima* is high in urban areas; this species is an alien invasive species originating from the subtropical zone of east south Asia, and populations have increased in recent years, presumably because of global warming (Song 2005).

Outbreaks of specific species, as now observed in *L. delicatula* in Korea, are unpredictable (Wilson 1987). Furthermore, no natural enemy of *L. delicatula* seems to exist in Korea. Thus, farmers use pesticides to control them in vineyards (Park et al. 2009). However, the use of pesticides kills natural enemies of other grape pests and *L. delicatula* can repopulate pesticide-sprayed areas from nearby forested areas, which contain suitable host species. Knowledge on behavior and host plant preferences is critical to develop novel and effective pest management strategies.

A relationship between host plants, enemies of insects, and insects is a central focus in ecology. The range of host plants can be broad or narrow, depending on the insect species (Bernays and Chapman 1994; Schoonhoven et al. 1998). Since insects have serious effects on the survival and density of host plants, insect regulation is one of the most manageable ways to preserve the host plant population (Prevost 2002). The effects of insects on host plants are specific (O'Reilly and Farmer 1991; Hedlin et al. 1980; Amirault and Brown 1986; Turgeon 1989; McClure et al. 1996), and confirmation of specific relationships between insects and host plants is needed to control the insect population. Host specificity can change over time or according to the developmental stage of the insect; studies on insect-plant relationship dynamics can help predict the time and degree of damage likely to be caused by insects feeding on host plants (Prevost 2002).

The main goal of this study was to determine if there are seasonal changes in *L. delicatula*'s host plant preferences. Specific objectives were to determine 1) which plants are used for laying eggs, 2) when eggs hatch, 3) where nymphs move after hatching, and 4) which plants nymphs and adults prefer. This information will help predict the movement and behavior of *L. delicatula* over time, thereby potentially allowing for pesticide-free control strategies.

Materials and methods

Study Site

This study was performed from April to December 2009 at Seoul National University (SNU), in Seoul, which is located in the west-central part of the Korean Peninsula. The size of the campus was ca. 100ha and constructed in 1976. Big trees in the campus are older than 40 years. *Lycorma delicatula* populations have been prevalent at SNU since 2008. Summer (from June to August) in Korea is hot (average 24°C) and humid (average rainfall of 270 mm/month), while winter (from December to February) is cold (average -1°C) and dry (average rainfall of 24 mm/month) (Fig. 1).

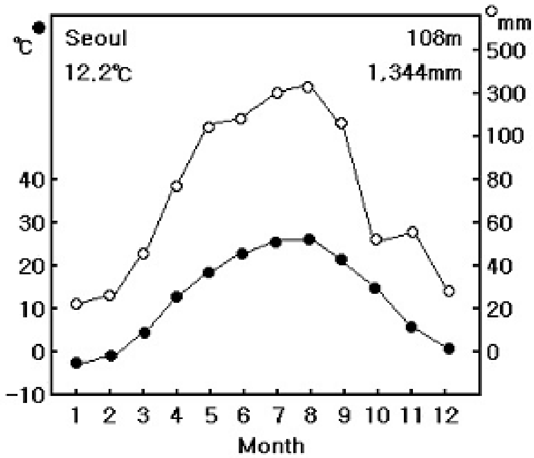

Fig. 1 Climate diagram of Seoul. Data from Korea Meteorological Administration (2000).

Egg laying host plant preferences

We surveyed most trees in SNU for oothecae and recorded the tree species and average size of oothecae on bark of tree trunks in April 2009. Furthermore, we recorded the locations of oothecae on those tree species, as well as the characteristics (smooth or rough; Stephenson 1989) of the bark surface onto which the oothecae were deposited.

Hatching and movement of nymphs on host plants

To determine hatching time and moving pattern of nymphs, we searched trees whose trunk has at least 3 m interval from the bottom to branched height and relatively homogeneous surface. We selected a *Betula platyphylla* tree whose trunk was upright with a first branch higher than 3 m and with many discernable oothecae on the trunk. We marked 16 oothecae and monitored between 0.3 m and 3 m height of the trunk for egg hatching at intervals of 3 hrs, from 0500h to 2300h, for 8 days starting on 8 May, 2009, when the first nymphs were observed on this tree.

To determine the moving patterns of nymphs, nymphs on the trunk of above *B. platyphylla* tree from 0.3 m above the ground to 3 m height were counted at 3 hr intervals from 0500h to 2300h on the 8th May, 2009.

To check where nymphs moved, we selected two *B. platyphylla* var. *japonica* trees and placed two sticky traps, which was designed for fly trap and sold in general stores, per tree on 22 May, 2010. One trap was set at a trunk height of 0.1 m, while the other was set at minimum height of 1.5 m, which has no branches. Traps were recovered the next day.

Morphology of the arolia

To find relationship between morphological change and staying interval on a tree, we checked the morphological change of arolina. Nymphs of 1st and 3rd instar stages and adults were collected to photograph the arolium using a scanning electron microscope (JSM-6040, JEOL, Tokyo, Japan) at Seoul Science Park. Collected samples were air-dried and fixed on a copper mount with a tape. Fixed samples were coated with gold.

Changes in host plant preference according to life stage

Life stages were defined as having a particular host preference if they were found living on the plant. From 16 July (3rd instar stage) to 1 November (adult stage), the host plant preference of insects was monitored on total 23 trees (8 families, 13 species, Table 1), which are known host plants (Park et al. 2009). We set two sticky traps around the tree trunks at heights of 0.1 m and 0.5 m from the ground. Traps were recovered after 3 days and set again 4 days after every recovery. We counted the maximum population density of *L. delicatula* in a 5 x 5 cm quadrat on the sticky trap. To determine *L. delicatula's* host plant preferences and the density of *L. delicatula* on each tree, the Shannon-Wiener diversity index was calculated based on tree species and numbers where *L. delicatula* was captured. In the calculation on the 20th April 2009, the number of oothecae present on total 61 trees of five species was included.

Table 1 Host plants selected to investigate changes in the host plant preferences of *Lycorma delicatula* according to lifecycle stage at SNU

Species	Family	Diameter of base (cm) of each tree
Acer saccharinum	Aceraceae	7.9
Acer palmatum	Aceraceae	10.8, 11.5
Betula platyphylla	Betulaceae	9.5, 14.8, 22.3
Cornus officinalis	Cornaceae	7.6
Cornus kousa	Cornaceae	10.5, 12.4
Cornus controversa	Cornaceae	23.1
Elaeagnus umbellata	Elaeagnaceae	5.4
Syringa vulgaris	Oleaceae	6.7, 7.0, 10.5
Pinus densiflora	Pinaceae	15.6, 19.1
Pinus strobus	Pinaceae	21.2
Phellodendron amurense	Rutaceae	15.5
Evodia daniellii	Rutaceae	36.3
Ailanthus altissima	Simaroubaceae	8.4, 16.2, 21.6, 31.2

Results

Location of eggs and their hatching characteristics

Listed in order of most to least abundant, we found *L. delicatula* oothecae on the trunks of *Zelkova serrata*, *Acer palmatum*, *Populus alba, Prunus serrulata* var. *spontanea*, *P. yedoensis*, *B. platyphylla* var. *japonica*, *Syringa vulgaris*, and *Evodia daniellii*, which were representative species in numbers at SNU (Table 2). Even though *L. delicatula* oothecae on *A. altissima* were much more, this species was not listed in Table 2 because tree number of this species was relatively very small. Most oothecae were on the smooth surface of the trunk at a height of 1 ~ 3 m. However, the trunk surface of *Prunus* spp. was rough at this height, and oothecae were found only on high of 13 m, small branches with smooth surfaces. On inclined tree branches, oothecae were found on the down-side or in hollow places.

Table 2 Oothecae of *Lycorma delicatula* on representative trees at SNU

Species[3]	No. of Trees	Average DBH[1] (cm)	Average No. of Oothecae	1 SD[2] of Oothecae
Zelkova serrata	16	6.2	29	28.8
Acer palmatum	23	4.1	21	18.6
Populus alba	4	14.7	15	9.7
Prunus serrrulata var. *japonica*	2	6.5	15	0.0
Prunus yedoensis	14	6.8	9	9.7
Betula platyphylla	2	17.4	9	5.7

[1]: diameter at breast height, [2]: standard deviation, [3]: tree numbers of these species at SNU are more than 20.

Sixteen oothecae were monitored at 3-hr intervals for 8 days. Eggs of two oothecae didn't hatch until the last day of this study. Total 211 eggs hatched between 0500h and 0800h. All eggs in one ootheca hatched simultaneously. However, eggs in different oothecae hatched on different dates (Fig. 2). The number of hatching eggs decreased on 11 May, and no eggs hatched on 12 May. The daily average temperature was low on 11 May (13.6^{o}C), as compared with 16.5^{o}C on 10 May. Furthermore, on May 11, it was cloudy in the morning and raining in the afternoon (30 mm rainfall) the next morning (6 mm rainfall on 12 May). The weather on 13 May was sunny even though the daily average temperature was low (13.9^{o}C), indicating that precipitation may have an effect on egg hatching. Even though the maximum amount of hatching occurred on 10 May, the peak of the observed total number of nymphs on the trunk of a *B. platyphylla* tree was on 11 May (Fig. 3), indicating the wind effects of a rainy day. No eggs hatched on 12 May, but the same number of nymphs as observed on 10 May were present on the trunk. The average wind velocity on the 10, 11, 12, and 13 May 2009 was 5.7, 11.4, 8.0, and 12.1 m/sec, respectively.

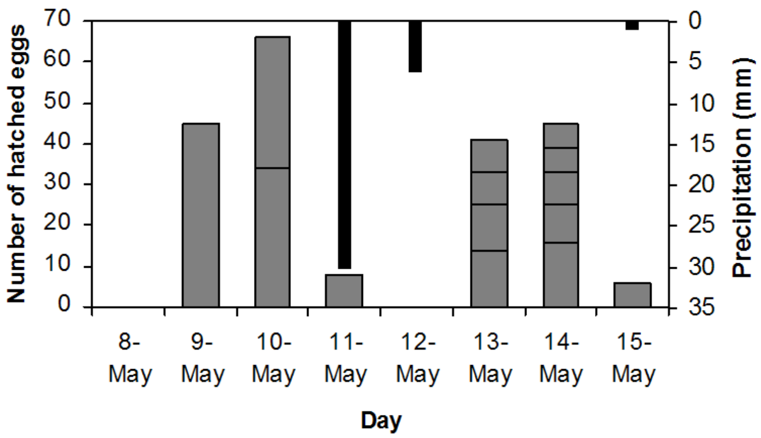

Fig. 2 Number of hatching eggs on one *Betula platyphylla* tree and daily precipitation as a function of time. The segment in the bar indicates hatched eggs from the same oothecae.

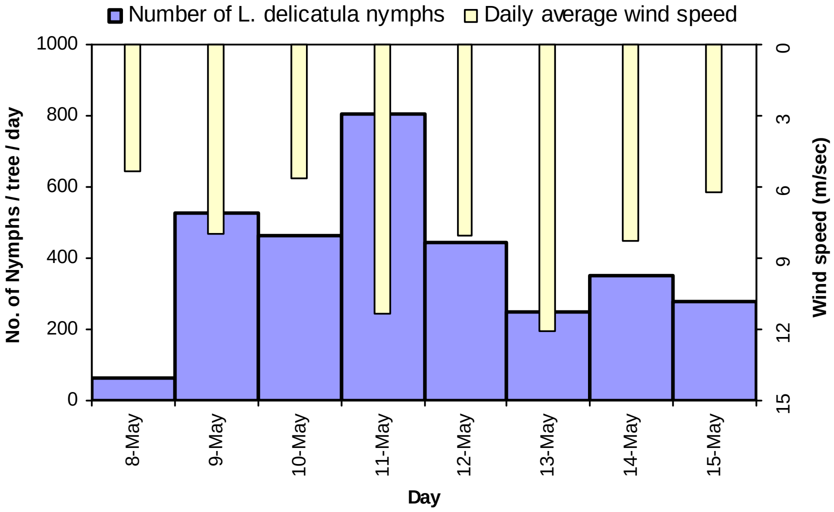

Fig. 3 Number of first instar nymphs on the trunk of a *Betula platyphylla* tree and daily average wind speed during the egg hatching period.

Movement of nymphs

Nymphs emerging from eggs headed upwards. They climbed up the trunk towards the leaves; no nymphs descended down the trunk towards the ground (Fig. 4). Two hundred twenty-eight nymphs were trapped on the lower sticky trap and 40 nymphs on the higher sticky trap on a tree between 1100h on 22 May to 1100h on 23 May. The nymphs caught in the upper trap were nymphs that hatched on 23 May. This upward movement was observed until the adult stage, when the nymphs develop wings. From 8 May to 15 May, nymphs were observed on the tree trunk mostly between 0800h and 1400h with a peak number observed at 1100h (Fig. 5). Most nymphs were observed on the leaves and only few were on the tree trunk at night. This cycle in the number of nymphs on the tree trunks occurred on a daily basis. Nymphs observed at 0800h had hatched from eggs. They started to climb the tree soon after hatching, and during this process, some nymphs fell off the tree. When they located the trunks of trees from the ground, they started to climb the tree again. Hatching nymphs started to arrive at the leaves at 1100h, and most nymphs had reached the leaves before 1700h.

Fig. 4 Nymphs on sticky traps. The 'A' trap was set 1.4 m above the 'B' trap on the same *B. platyphylla* var. *japonica* tree; the arrow indicates the upward direction. These photos show the upwards directional movement of the nymphs.

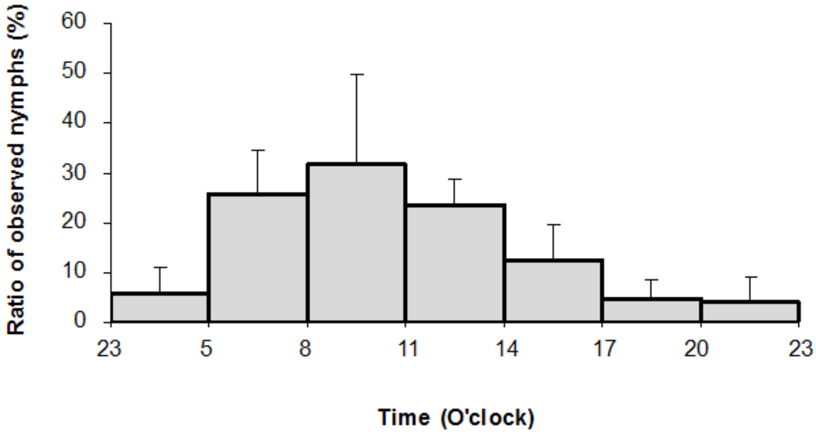

Fig. 5 Diurnal changes in the average number of nymphs observed on tree trunks. Error bar indicates 1 standard deviation.

Change in arolium morphology with growth

The arolium structure is an important determinant of *L. delicatula's* ability to climb trees. The arolium consists of a sticky lip, claw, and a small airspace (Fig. 6). The tarsal claw and sticky lip of adults were about 5-fold and 6-fold as long as those of 1st instar stage nymphs, respectively (Table 3).

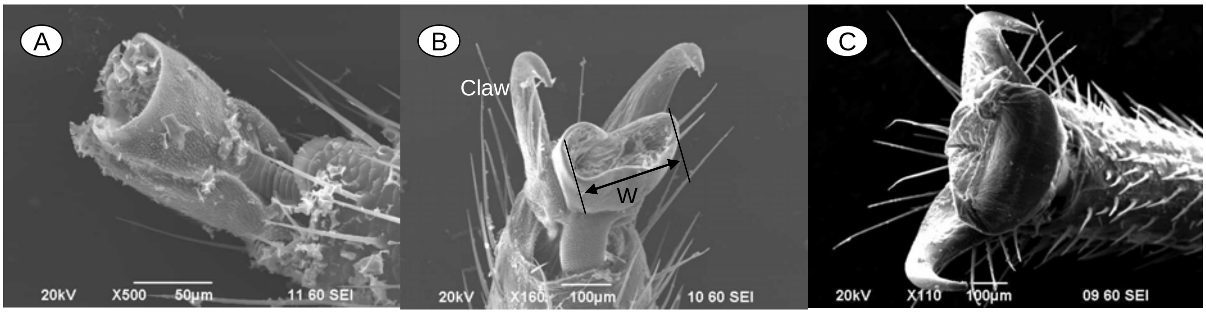

Fig. 6 Scanning electron microphotographs of the pretarsus of the middle leg of *Lycorma delicatula*. The pretarsus of A: a 1st instar stage nymph, B: a 3rd instar stage nymph, and C: an adult. W: width of the sticky lip.

Table 3 The length of tarsal claw and sticky lip in three developmental stages of *L. delicatula*. n=3

	Average length (SD) (µm)	
Stage	Tarsal claw	Sticky lip
1st instar	100 (2.5)	77 (16.1)
3rd instar	215 (55.3)	208 (45.0)
adult	525 (75.6)	480 (89.1)

Changes in host plant preference over time

On the 16th of July, nymphs of *L. delicatula* were collected on 18 of 23 marked trees and on 12 of 13 species of marked trees (Fig. 7). The number of trees on which *L. delicatula* were collected peaked on 26th July, then decreased with time, and remained relatively constant at about 5 trees starting on 6th September. The change in tree species use changed in a manner similar to tree number. From 6 September until 1 November, *L. delicatula* adults were collected only on *A. altissima* and *E. daniellii* trees.

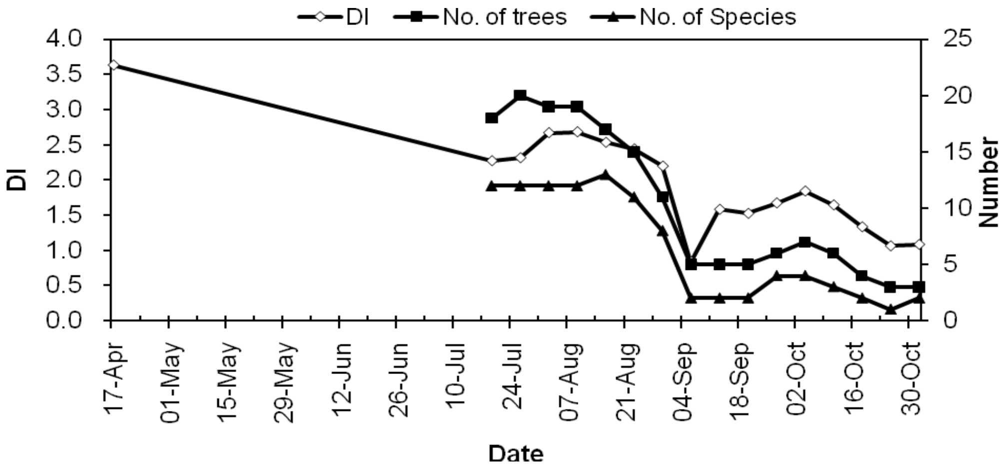

Fig. 7 Changes in the diversity index and number of tree and species occupied by *Lycorma delicatula* nymphs or adults. The diversity index was calculated based on the numbers of nymphs or adults on the trees.

We calculated diversity indexes to determine host plant species preferences and the density of *L. delicatula* on each tree. When we used oothecae data from April, the Shannon-Weiner diversity index was 3.63. This value decreased to 2.27 on 16 July, increased to 2.68 on 9 August, decreased again on 6 September, and then remained at approximately 1.5 with small fluctuations, indicating they prefer less species and more trees of those species with growth.

The total number of *L. delicatula* collected on monitored trees decreased dramatically from 397 individuals during 16~19 July to 0 in the period of 5~8 November (Fig. 8). Even though there were only four trees of *A. altissima*, the number of *L. delicatula* collected on this tree species comprised approximately 50% of the total number of *L. delicatula* collected until 30 August and increased to about 80~100 % thereafter.

The average number of *L. delicatula* on one *A. altissima* tree was 49 individuals /25 cm^2 in the first period of 16-19 July – a value 4.6 times that on other tree species. The average number of *L. delicatula* on all species of trees decreased with time, as did the total number collected. From 31 August, the average number of *L. delicatula* on tree species other than *A. altissima* was less than 1; there were 10~20 times more *L. delicatula* on *A. altissima* than on other species.

Discussion

Knowledge of the life cycle of an organism is very important to understand that organism's behavior. Critical life history events must correspond to appropriate seasonal cycles in order to avoid lethal temperatures or other environmental extremes, to coordinate the timing of reproductive cycles, to avoid predation through simultaneous mass emergence, and to meet a multitude of other requirements to maintain ecological and biological viability (James and Jesse 2005).

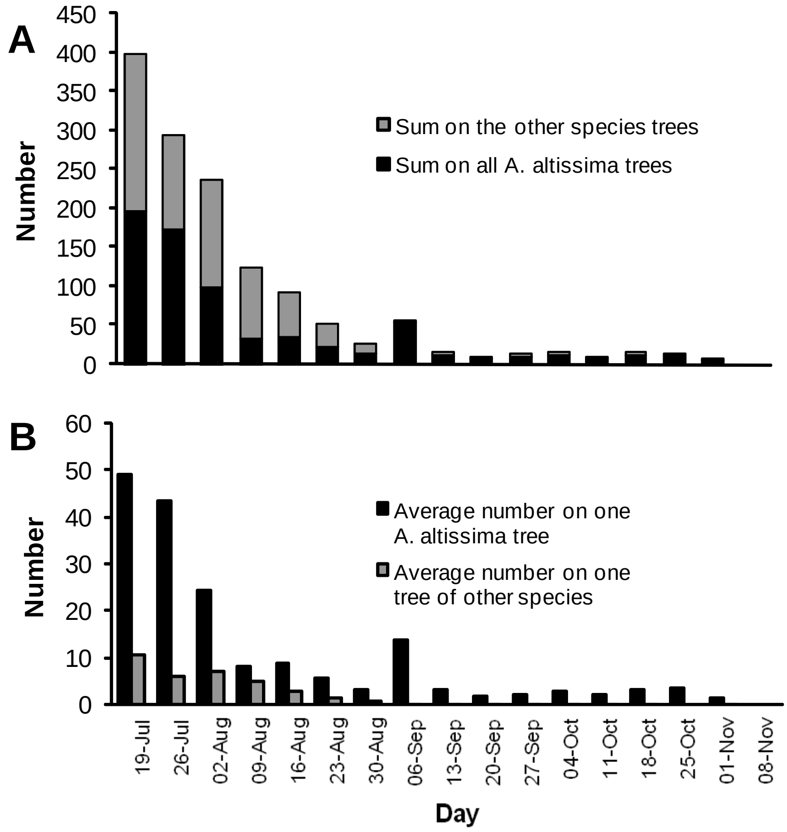

Fig. 8 Weekly changes in the number of *Lycorma delicatula* collected on *Ailanthus altissima* and 13 other tree species. A: sum of *L. delicatula* on four trees of *A. altissima* and on 19 trees of 13 species, B: average number per *A. altissima* trees; average number on other tree species.

Lycorma delicatula is known to prefer *A. altissima* as a host in its native area (Sanyang 1992) and to harm this tree (Li and Tao 1980; Yao and Liu 1993). In Korea, *A. altissima* is an alien invasive species that is rapidly expanding its distribution (Song 2005). The increase in the distribution of this preferred host plant of *L. delicatula* might be the reason why a rapid expansion of *L. delicatula* has been observed in Korea in recent years. However, Park et al. (2009) reported that the adults of *L. delicatula* depended on more than 10 tree species. Our results indicate that adult *L. delicatula* have the strongest preference for *A. altissima* just before laying eggs. Even though *L. delicatula* prefer *A. altissima*, they can use other species if *A. altissima* is not available, which may be why they feed on and damage grapes in orchards. An understanding of the life cycle characteristics and host plants preferences of *L. delicatula* may aid in the development of strategies to prevent *L. delicatula* damage to grapes.

In this study, we found two cycles of *L. delicatula* behavior. One is a falling-ascending cycle within a short period of one or two days. The other is the host plant preference cycle with a 1-year period. These two cycles are very informative to control the outbreak of *L. delicatula*.

Falling-ascending cycle

Lycorma delicatula nymphs and adults climb trees, strong herbs, and other plants. When they encounter some physical obstacle, they stop moving and jump to another place. They escape mostly by climbing or walking on tree trunks, while adult *L. delicatula*, which have wings, require some stimulation to encourage flight. This walking or jumping character may be related to the leg length and the state of development of the arolium (Fig. 6). The length of an adult *L. delicatula* from the anterior margin of the head to the apex of the folded wing is 24.0–26.5 mm for females and 20.5–22.0 mm for males, with a leg length of 18–22 mm in females and 15–18 mm in males (Frantsevich et al. 2008). *L. delicatula* has tarsal adhesive pads (arolia), which are highly dynamic organs that play an important role in locomotion. Many insects combine fast running performance with strong resistance to detachment forces. This capacity requires the effective control of attachment forces at the tarsus and pretarsus (Walter and Thomas, 2004). Even though the arolium is principally involved in walking and sensing in some species (Arnold 1974), it is an elaborately sculpted, adhesive organ and is particularly important for climbing in *L. delicatula*.

Even though just-hatched nymphs of *L. delicatula* have a small claw and sticky lip on their arolia, they can climb trees to a height of more than 5 m (we monitored trees higher than 5 m to the closest leaf from the bottom). Because they have small arolia, they are easily dislodged from leaves by the wind. Fallen nymphs climb trees, plants, or other physical objects when they encounter these on the ground. It is possible that this falling-ascending behavior may be a strategy to select host plants, but may, on the other hand, be due only to physical factors, such as wind. In the 1st instar stage, nymphs use a variety of plants and even climb annual herbs. Their legs and arolia become bigger and stronger as they grow, and can stick on the tree surface more firmly. This means that their falling-ascending cycle becomes longer because they fall less frequently (Fig. 9).

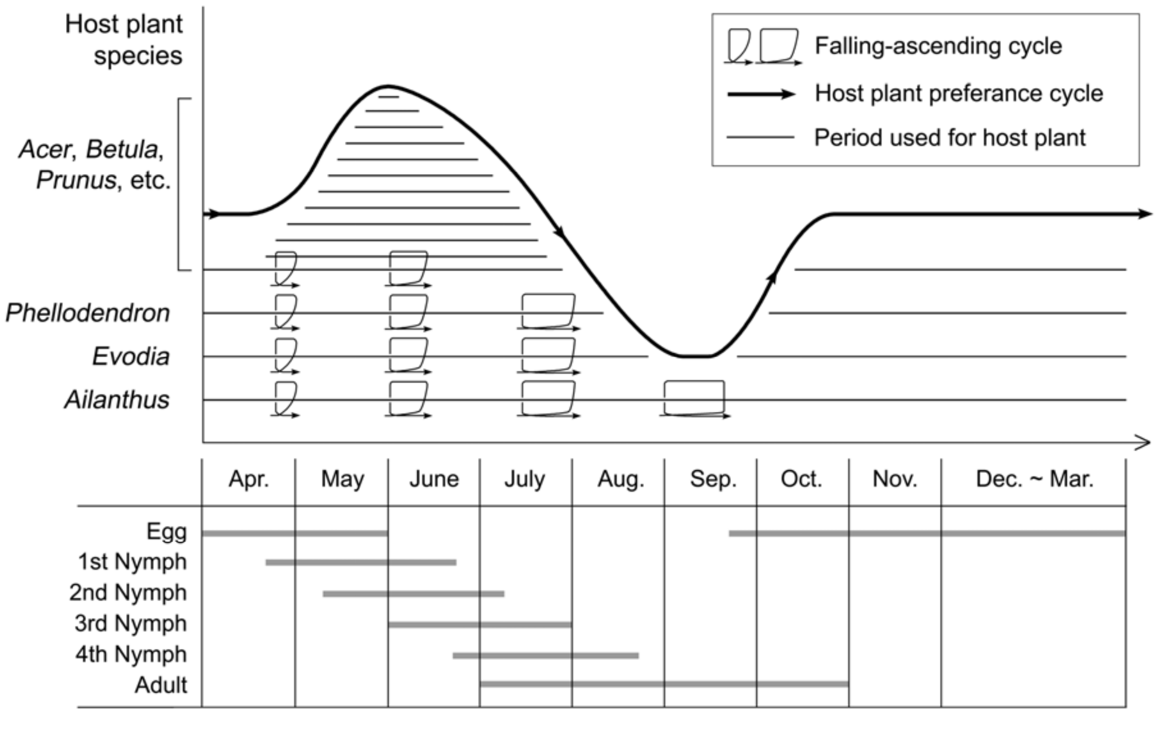

Fig. 9 Summary of the two cyclic behaviors of *Lycorma delicatula*: the falling-ascending cycle and the host plant preference cycle. Life cycle data is from Park *et al*. (2009).

Host plant preference cycle

Even though *Lycorma delicatula* is a pest species of *A. altissima*, Li and Tao (1980) and Yao and Liu (1993) insisted that this insect is a generalist and does not live solely on *A. altissima*. Their opinion might be based on the distribution of *L. delicatula* nymphs on tree species.

However, our observations revealed that there is a specific time (just before laying eggs) when adult *L. delicatula* strongly prefer only one or a few species of tree, namely *A. altissima*, *E. daniellii*, and *P. amurense*. There are red dots on the wings of *L. delicatula*. This red color might be warning color and may indicate that they have some toxic substance in their body. *Ailanthus altissima*, their preferred host, contains high concentrations of cytotoxic alkaloid chemicals (Ohmoto et al. 1981; Anderson et al. 1983). Furthermore, the second-most preferred tree species, *E. daniellii*, is used in oriental medicine to kill insects (Lee 1979). Other species heavily damaged by adult *L. delicatula* (Park et al. 2009) are also used as materials for oriental medicine (Lee 1979). Therefore, *L. delicatula* might generally prefer plant species with toxic secondary metabolites, and may even use those for their own defense. The exception to this is *Vitis* spp. (grapes), which does not contain toxic alkaloids. Their presence on grapes might indicate that they were not able to find toxic host plant species.

The ovipositional patterns of an insect on different host plants can be explained by inherited general criteria for host plant preference, not necessarily species-specific criteria (Bernays and Chapman 1999). In the case of *L. delicatula*, this general criterion might be the smooth surface of the tree trunk. Oothecae of *L. delicatula* were found on various trees with a smooth surface structure (in this study and Park et al. 2009). Nymphs in the 1st instar stage appeared to feeding almost every plant that they encountered on the ground, indicating that *L. delicatula* is a broad generalist at this stage. These 1st instar nymphs can move rapidly and start to show their preferences for specific host plants as they grow. At this point, the red dots on the incomplete wings start appearing. The climax of host plant preference is just before laying eggs. *L. delicatula* eggs have to defend themselves, either by having a physical defense structure (such as a hard shell) or chemicals, against predators, e.g., birds. These eggs may contain toxins sequestered from *A. altissima*, which would explain why these insects expand their range of host plants in the young instar stage and then narrow their host plant preference just before laying eggs.

Implications for the control of Lycorma delicatula *populations*

We found two cycles of *L. delicatula* behavior (Fig. 9). These can potentially be exploited to control this insect. Young nymphs of *L. delicatula* fall easily from trees and ascend nearby trees. This behavior makes it possible to trap almost all of the young nymphs on a particular tree by placing a trap at the base of the tree. However, it is not easy to trap all nymphs because they are generalists at this stage.

When they mature, their host plant preference narrows to a few plant species. The density of preferred plants in Korea is very low, with the exception of grapes; a large number of nymphs feeding off a grape plant can potentially kill it. Even though *L. delicatula* adults can fly to other trees, they prefer to move up trees by walking. If traps are set at a height of about 10 cm on the preferred tree, this insect can be trapped easily.

The most effective method to control the population of *L. delicatula* without the side effects of killing beneficial insects in orchards (Park and Lee 2009) appears to be the application of physical trapping methods. We used sticky traps in this study and found that these were very effective. The best location to set traps is at the base of preferred host species, such as *A. altissima, E. daniellii, P. amurense*, and *B. platyphylla* from August to October.

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