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SHORT COMMUNICATION

Urban landscape and forest vegetation regulate the range expansion of an exotic lace bug *Corythucha marmorata* (Hemiptera: Tingidae)

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Abstract

Landscapes and vegetation are critical factors in dispersion of exotic insects and expansion of their range. However, few studies have addressed how the surrounding landscape affects the establishment of exotic insects. We assessed the relationship between establishment of an exotic lace bug *Corythucha marmorata* (Uhler) and the surrounding landscape in the northern edge of the lace bug's expanded range. We found that the lace bugs showed variability in their density among populations. Urban areas had a positive effect, while the natural forest vegetation had a negative effect on lace bug density, with a buffer range of 1–2 km. Moreover, their abundance decreased with distance from the source population. Our results suggest that natural forest landscapes in urban areas may inhibit the range expansion of invasive insects that feed on exotic plants growing in human-disturbed habitats.

Key words: invasive insects, Japan, *Solidago altissima*.

Numerous invasive insects that have become established in a new range have become serious agricultural or forest pests around the world (Sailer 1983; Worner 1994). The dispersal ability of exotic insects is crucial to their establishment and spread in new regions. Landscape elements are important environmental factors that influence the dispersal ability of herbivorous insects (Tscharntke & Brandl 2004). In addition, exotic insects often expand their habitat rapidly in the invaded range because of human activities (Kiritani & Morimoto 2004; Estay *et al.* 2012). Habitats unsuitable for invasive insects, which connect host-plant patches, may facilitate or limit their dispersal (Davalos & Blossey 2011), thereby positively or negatively affecting their population growth.

The lace bug *Corythucha marmorata* (Uhler), one of the most abundant herbivores of *Solidago* spp. in its native North America (Cappuccino & Root 1992; Fontes *et al.* 1994), was first recorded in Nishinomiya City of Hyogo Prefecture in western Japan in August 2000 (Tomokuni 2002). Its major host-plant, *Solidago altissima*, was also introduced to Japan 100 years ago, and is now abundant throughout the country. In Japan, *C. marmorata* is also known to feed on several other wild plants of the family Asteraceae (e.g. *Erigeron* spp. and *Ambrosia* spp.) (Kato & Ohbayashi 2009) and *Calystegia japonica* (Convolvulaceae) (Y Sakata, personal obs., 2014). Since the first record in Japan, *C. marmorata* has expanded its range concentrically and now constitutes a serious pest of both chrysanthemum and sweet potato (Kato & Ohbayashi 2009; Sakata *et al.* 2014). In addition, *C. marmorata* has recently been reported in China and Korea (Kai *et al.* 2012; Yoon *et al.* 2013). On the Kii Peninsula and Shikoku Island, the lace bugs expanded their range rapidly: it took only three to four years to expand over the entire peninsula (9.9×10^3 km^2) and island (1.8×10^4 km^2) (Kato & Ohbayashi 2009). Thus, the rapid expansion of the lace bugs may have occurred because of the combined effects of host-plants colonizing roadside areas, the lace bug's dispersal ability and transportation assisted by automobiles. Therefore, the surrounding landscape, including their preferred host-plants, may determine their expansion and the variability in their abundance, given that human agents may promote their establishment.

According to the records of prefectural Plant Protection Offices in northern Japan, the lace bug had reached Niigata Prefecture in 2007, Fukushima Prefecture in 2008 and Miyagi Prefecture in 2013, while it has not been

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reported in Yamagata Prefecture (Niigata Prefectural Plant Disease and Insect Control Station 2007; Fukushima Prefectural Plant Disease and Insect Control Station 2008; Miyagi Prefectural Plant Disease and Insect Control Station 2013). Thus, it can be inferred that the northern edge of the lace bug distribution in 2014 was between Niigata and Yamagata prefectures. In this area, the lace bug density may be highly variable among populations because this is the northern edge of their range. The distance from the southern source-populations of lace bugs (i.e. Niigata and Fukushima) may have affected the establishment of the lace bugs. In addition, the surrounding landscape of *S. altissima* populations may have affected the lace bug abundance across the expanding populations. In this study, we investigated how the surrounding landscape affects the habitat expansion of the lace bugs by a field survey on the distribution of *C. marmorata* in Yamagata and Niigata. This study included analysis of the relationships between lace bug density and the surrounding landscape, and will be informative for understanding the interaction between landscape and lace bug establishment in regions at the present northern limit of their distribution, and for preventing them from becoming a serious agricultural pest in the new regions.

We selected five sites in Yamagata and four sites in Niigata (Fig. 1) for survey. All of the sites were located at the range of low altitude (mean ± SE = 61.42 ± 20.26 m). We randomly selected three ramets per genotype for ten genotypes of *S. altissima* that were distinguished by clumped populations. We measured the number of lace bugs, damage rate by lace bugs and the number of leaves of *S. altissima* plants in September 2014, which allowed us to quantify the accumulated feeding scar of lace bugs during summer when they are most active. The damage level was evaluated by classifying damaged leaves (those with yellow scars induced by the lace bug feeding) into four levels: (1) no damage; (2) $<33\%$ damage of total leaf area; (3) 33–66% damage; and (4) $>66\%$ damage. Then, we counted the number of leaves for each damage level, summed the values of all four levels, and finally divided this figure by the total number of leaves.

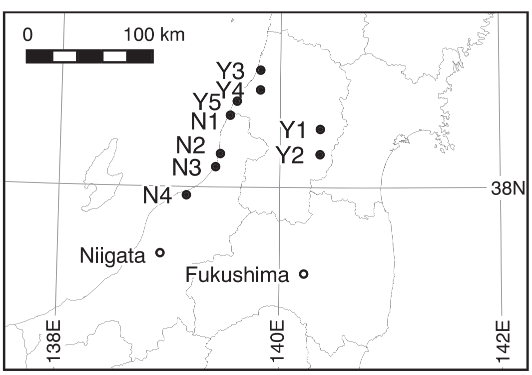

Figure 1 Field survey sites of *S. altissima* populations. Open circles indicate the center of gravity of Niigata and Fukushima prefectures.

Using QGIS software (Quantum GIS Development Team 2012), the area of each of ten classes of vegetation around each site was calculated for three different scales by creating circle buffer polygons with radii of 0.5, 1, 2 and 5 km. These buffer sizes were selected so that habitats that critically affect the lace bug density at both localized and broader scales were included. Classes of vegetation were identified by the vegetation map provided by the Ministry of Environment. The ten classes were: (1) Alpine natural vegetation; (2) Lingonberry-Spruce natural vegetation; (3) Lingonberry-Spruce substitution vegetation; (4) Beech natural vegetation; (5) Beech substitution vegetation; (6) Camellia natural vegetation; (7) Camellia substitution vegetation; (8) River bank, wetland, sand dune vegetation; (9) Plantation, farmland vegetation; and (10) Urban land (excluding water areas). Combined vegetation class (forest vegetation, classes 1–7) was also created. In addition, since we did not know the exact location of the first appearance of the lace bugs in each prefecture, distances from the center of gravity in both Niigata and Fukushima prefectures, as a representative location of the prefecture, to each survey site were calculated using QGIS software. We explored factors influencing the number and the damage level of lace bugs using generalized linear mixed models (GLMMs). Lace bug abundance and damage were set as response variables, and the area of all the vegetation classes and distance from both Niigata and Fukushima were set as explanatory variables. The natural logarithm of the leaf number was entered into the model as an offset term to control for the differing number of leaves on each ramet. We included individuals nested within a population as a random effect. Because the scale of the surrounding landscape that might affect lace bug abundance was unknown, we explored the scale with the highest goodness of fit when added to the model using Akaike's information criterion (AIC) as a measure for all vegetation classes. We selected the best model with the lowest AIC value. All of the analyses were conducted using the lme4 package (Bates *et al.* 2011) of R 2.13.1 (R Development Core Team 2013).

The abundance and damage of the lace bugs varied among populations, and they had colonized all the sites in Niigata (but only on one ramet in site N1) and at Y1, Y2 and Y4 in Yamagata (Fig. 1). There was a negative effect of the distance from the center of gravity of both prefectures to each site on lace bug abundance and damage (Table 1). This is consistent with our predictions that the lace bugs are currently invading these areas and

Table 1 Results of the generalized linear mixed model (GLMM), which predicts lace bug abundance (upper half) and damage level (lower half)†

Variables	Estimate	SD	z value	*P* (>|z|)
(Intercept)	4.79E +00	2.42E + 00	1.98	0.05
Niigata	–1.43E–02	7.45E–03	–2.06	0.04
Fukushima	–6.62E–02	1.83E–02	–3.61	0.0003
Urban (2 km)	7.29E–07	2.24E–06	3.25	0.001
Beech (1 km)‡	–4.60E–06	1.43E–06	–3.22	0.001
(Intercept)	6.34E + 00	2.00E + 00	3.17	0.002
Niigata	–1.03E–02	6.22E–03	–2.10	0.04
Fukushima	–8.02E–02	1.53E–02	–5.26	<0.0001
Urban (2 km)	7.77E–07	1.79E–07	4.34	<0.0001
Beech (1 km)‡	–5.00E–06	1.24E–06	–4.03	<0.0001

† Results are explained by the distance from the center of gravity of Niigata and Fukushima prefectures, and urban area within radius of 2 km and beech class natural vegetation area within radius of 1 km.
‡ The other vegetation classes were not selected in the best model.

that their abundance varies among the invading populations.

Among the ten vegetation classes, the area of the class 'urban landscape' enhanced both lace bug abundance and damage, while the class 'beech natural vegetation' negatively affected them in all the buffer ranges. The rest of the vegetation classes, including the 'combined forest vegetation', had no effect on the lace bug abundance or damage. The model showed best fit when the buffer distance (i.e. diameter of the buffer around each site) was 2 km for urban area and 1 km for beech natural vegetation (Table 1). We showed only the damage level of the lace bugs in Figure 2, because the lace bug abundance exhibited the same trend as the damage level: increasing with an increase in urban area and decreasing with an increase in beech forest area. We found that lace bugs have established sites closer to the source populations and are likely to expand to *S. altissima* populations in urban areas. Because they need to disperse to new host-plant populations to expand their range, and because *S. altissima* and other host-plants are abundant in human-disturbed habitats, the urban landscape would accelerate their expansion by facilitating their dispersal. On the other hand, the beech forest vegetation at a scale of radius 1–2 km may inhibit their dispersal and serve as a barrier to their expansion. The reason why beech forest vegetation had a negative effect on lace bug abundance is probably because the vegetation includes broad-leaved deciduous tree species, which is the dominant natural vegetation type in the Tohoku region, and is less disturbed by human activity compared to the vegetation classes 5–7.

Although only one or two years were needed for the lace bugs to reach the adjacent prefecture in the southern area in the Kinki and Shikoku regions (Kato & Ohbayashi 2009), it took five years for the lace bugs in the northern area in Tohoku region to reach Miyagi prefecture after reaching Fukushima (100 km between the prefectural plant protection offices), indicating that lace bug expansion is slower in the northern region. The lower temperature may have caused slower development as shown in other lace bug species (Tsukada 1994), and have led to fewer generations per year in the northern region. Although it is predicted that they should expand their range throughout Japan in the near future, our results suggest that natural beech forest vegetation adjacent to the urban areas may decelerate, and prevent the range expansion of the lace bugs. Our findings have important implications for understanding invasion mechanisms and for controlling the dispersal of this urban invader. Further study at smaller spatial scales, conducting experiments such as mark-release-recapture experiments to evaluate the effect of distance between host-plant patches on lace bug abundance, may be critical to preventing the range expansion of this agricultural pest.

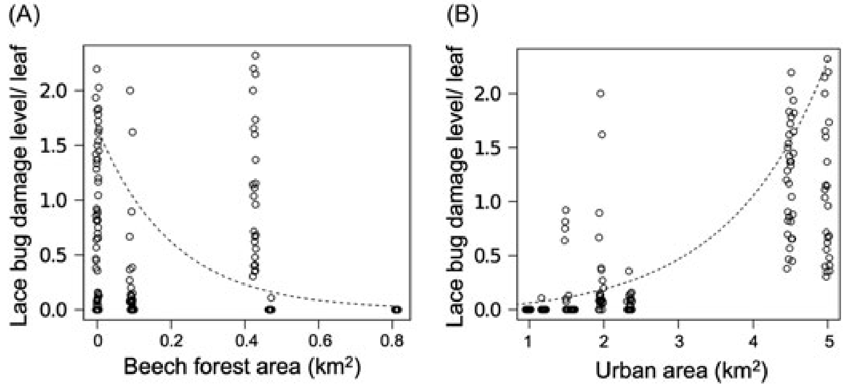

Figure 2 Relationship between lace bug damage level and (A) urban area within radius of 2 km, and (B) beech class forest area within radius of 1 km. Dashed curves represent a significant relationship between lace bug damage level and the two landscape areas.

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