Northward range expansion by *Nezara viridula* (Hemiptera: Pentatomidae) in Shikoku and Chugoku Districts, Japan, possibly due to global warming

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Abstract
Field surveys and light trap catches of *Nezara viridula* and *N. antennata* (Hemiptera: Pentatomidae) in Shikoku and Chugoku Districts, Japan showed that *N. viridula* is now distributed along the northern coastline of Shikoku District, and in Yamaguchi Prefecture, and along the northern coastline of Shimane Prefecture, south of Izumo, Chugoku District. The present data together with previous reports suggest that the northward range expansion of *N. viridula* is possibly due to global warming because the monthly mean temperature for January in newly invaded areas has exceeded 5°C in recent years, for example, since 1986 in Fukuoka, below which the winter mortality of *N. viridula* adults becomes higher. Around the northern limit of *N. viridula* in Shimane Prefecture, it was not found in April–August 2008 because the monthly mean temperature for January 2008 fell below 5°C, below which the winter mortality of *N. viridula* becomes higher. Thus, the northern limit retreated depending on winter temperature. We confirmed the absence of *N. viridula* from 1979 until August 2008 in Izumo, Shimane Prefecture, and in 2007–2008 in Tottori Prefecture. Most areas along the southern seacoast in Shikoku District were occupied only by *N. viridula*, suggesting that it has replaced *N. antennata* by interspecific mating. In the Chugoku District, no area was occupied only by *N. viridula*, but it was more abundant than *N. antennata* in southern Yamaguchi Prefecture, indicating that *N. viridula* is now replacing *N. antennata* in that area.

Key words: Northward range expansion; *Nezara viridula*; *Nezara antennata*; global warming; interspecific mating

INTRODUCTION
Poleward range expansion is a common trend caused by global warming and has been documented in many insects (e.g., Parmesan and Yohe, 2003; Root et al., 2003). In Japan, northward range expansion has been reported mainly for butterflies (e.g., Yoshio and Ishii, 2001; Kiritani and Yamamura, 2003) and stink bugs (e.g., Musolin and Numata, 2003; Kiritani, 2007; Yukawa et al., 2007; Tougou et al., 2009). Among them, the range expansion by *Nezara viridula* (L.) (Hemiptera: Pentatomidae) is particularly a matter of some concern for agricultural production, because it is known as a serious pest of rice plants and various other crops (e.g., Kiritani, 1971; Todd, 1989; Panizzi et al.,...
2008). In addition, *N. viridula* has caused the local extinction of its allied congener, *Nezara antennata* Scott, as a result of their interspecific mating, which prevented *N. antennata* from intraspecific mating because *N. antennata* was overwhelmed in abundance by *N. viridula*, which has higher reproductive potential than *N. antennata* under warm conditions with sufficient food resources, i.e., rice plant (Kiritani et al., 1963; Kiritani, 1971). In contrast, interspecific mating may prevent *N. viridula* from establishing in newly invaded areas, because of the difficulty of finding conspecific partners under sparsely populated conditions in the initial stage of invasion. Thus, interspecific mating is detrimental to less abundant species.

On the basis of such information, the relative abundance of *N. viridula* and *N. antennata* has been surveyed intensively and successively at various localities in the Kii Peninsula, Honshu and northern Kyushu, Japan (e.g., Kiritani et al., 1963; Yukawa et al., 2007; Tougou et al., 2009). The results of field surveys, together with scattered collection records of *N. viridula* in the Kii Peninsula and Kyushu, clearly showed that *N. viridula* has been expanding its range northward since the 1960s, possibly due to global warming (Yukawa et al., 2007; Tougou et al., 2009). In addition, the present range of *N. viridula* in Kyushu coincides well with areas where the mean temperature in the coldest month, which is usually January (Japan Meteorological Agency, 2008), exceeds 5°C (Yukawa et al., 2007), which has been suggested to be the lowest thermal limit for the population of *N. viridula* to persist successfully (Kiritani et al., 1963). On the west coast of the Kii Peninsula, the northern limit of *N. viridula* was Arida City in the 1960s (Kiritani et al., 1963), but it was subsequently found in Sakai City and southern parts of Osaka City, about 70 km north of Arida City (Musolin and Numata, 2003; Yukawa et al., 2007). Recently, Tougou et al. (2009) confirmed that *N. viridula* expanded its distribution range northward to northern parts of Osaka Prefecture, about 85 km north of Arida City, and to Nantou Town (presently called Minami-ise Town; 34.30°N; 136.60°E), Mie Prefecture on the east coast of the Kii Peninsula. The distance, 85 km per 45 years from 1963 to 2008, means that *N. viridula* has been moving northward about 19 km per decade.

Thus, the northward range expansion by *N. viridula* has been confirmed in the Kii Peninsula and Kyushu (Yukawa et al., 2007; Tougou et al., 2009), but recent distributional information in Shikoku and Chugoku Districts has been inadequate, although some scattered collection records have been reported (Nakamura et al., 2001; Ohno and Nakamura, 2007). To fill the information gap on northward range expansion by *N. viridula* in Shikoku and Chugoku Districts, we investigated the presence or absence of *N. viridula* and *N. antennata* in various places in these districts and gathered collection records on *N. viridula*.

Based on these investigations, this paper intends to show the trend of northward range expansion by *N. viridula* in Shikoku and Chugoku Districts and to discuss the northward shift and southward retreat of its northern limit in relation to annual changes in winter temperatures.

**MATERIALS AND METHODS**

**Field survey.** The names of districts, prefectures, and localities in this paper are indicated in Figs. 1, 2, and 3. From 1972 to 1973, two authors, KK and TK, surveyed the presence or absence of *N. viridula* and *N. antennata* in various crop fields in many localities in Kochi, Ehime, and Tokushima Prefectures, Shikoku District (Fig. 2), and also on Awaji Island, Hyogo Prefecture (Fig. 3) (Kawasawa, 1974). From September to October 2007, we surveyed *Nezara* bugs in Tottori, Shimane, and Yamaguchi Prefectures, Chugoku District and in Sanda City, Hyogo Prefecture, east of Chugoku District (Fig. 3).

From April to September 2008, we concentrated our field surveys in Yamaguchi City and northern parts of Shimane Prefecture where *N. viridula* had been found in the 2007 surveys but the monthly mean temperature for January 2008 fell below 5°C, which might reduce the survival rate of overwintering *N. viridula* adults. We also surveyed *Nezara* bugs in Kagawa Prefecture in August 2008.

For each field survey, one to ten individuals randomly collected *N. viridula* and *N. antennata* adults by hand directly from cultivated plants, such as soybean, *Glycine max* (L.) Merrill and kidney bean, *Phaseolus vulgaris* L. (Fabaceae), eggplant, *Solanum melongena* L. (Solanaceae), sunflower, *Helianthus annuus* L. (Asteraceae), maize, *Zea mays* L., wheat, *Triticum aestivum* L. and rice, *Oryza
sativa L. (Poaceae), including rice ratoons after harvest. *N. viridula* and *N. antennata* are polyphagous and are known to occur commonly on these crops (e.g., Kiritani et al., 1963; Kiritani and Hokyo, 1970). In faunistic field surveys, one difficulty is the reliance placed on absence. A species may be erroneously recorded as absent when collecting has been insufficient or in the wrong growing season of crops, or when the species is rare. To overcome this difficulty, we visited several different crop fields in one area, and devoted one to three hours in each crop field, depending on the density of *Nezara* bugs because their population density was sometimes very low. Whenever we found adult

![Map of Japan](image1)

**Fig. 1.** Map of Japan (except Hokkaido, northern Honshu, and the Sakishima Islands), indicating districts, prefectures, and localities where the presence or absence of *N. viridula* is mentioned in this paper.

![Map of Shikoku District](image2)

**Fig. 2.** Map of Shikoku District, Japan, indicating localities where the presence or absence of *Nezara viridula* was surveyed in 1972–1973. Black circles were converted to double circles in several northern localities where the presence of *N. viridula* was confirmed after 2004.
Nezara bugs in a field, they were usually accompanied by eggs or larvae, so we regarded them as resident in that field.

The two Nezara species collected were identified based on the color of antennae and abdominal tergites, based on the description by Hasegawa (1954) and Kobayashi (1959).

**Light trap.** To monitor the occurrence of pest insects, light traps have been set in various localities in every prefecture of Japan. We examined Nezara bugs collected in light traps in Yamaguchi Prefecture from August to October 2007, in Shimane Prefecture from April to July 2008, and in Tottori Prefecture from August to October 2007 and July and August 2008. To confirm the absence of *N. viridula* from northern Shimane Prefecture, we also referred to data of annual catches of Nezara bugs in a light trap set from 1979 to 2008 in Izumo City, the data provided by the Fruit Tree Research Group, Shimane Prefectural Agricultural Technology Center.

**Literature survey and specimens examined.** We obtained distributional information on *N. viridula* from Kawasawa (1974), Nakamura et al. (2001), Ohno and Nakamura (2007), and annual reports on light trap catches of pest insects in Ehime Prefecture from 2004 to 2007. Specimens of Nezara bugs kept in Tokushima Prefectural Museum were examined by Mr. K. Ohara, who informed us about the collection data attached to the specimens.

**Possible distribution range of *N. viridula***

**Based on monthly mean temperatures for January.** As mentioned earlier, it is difficult for *N. viridula* to persist continuously in areas where the mean temperature in the coldest month of the year falls below 5°C (Kiritani et al., 1963). Based on this report and estimated meteorological data for 1961 and 2000–2008 at 386,555 quadrats of 1 km² in Japan (Japan Meteorological Agency, 2002, 2008), maps of the possible distribution range of *N. viridula* were drawn for 1961 and 2000–2008. We also indicated monthly mean temperatures for January 2008 for some selected areas directly on the map of Chugoku District in order to discuss the overwintering potential of *N. viridula* in the areas where it was found in 2007.

**RESULTS**

**Shikoku Districts**

In the 1972–1973 field surveys, the southern coast of Kochi Prefecture was occupied by only *N. viridula*, while it coexisted with *N. antennata* in mountainous areas (Fig. 2). The two Nezara bugs also coexisted along the west coast of Ehime Prefecture and the east coast of Tokushima Prefecture, but the northern limit of *N. viridula* was around Uwajima, Ehime Prefecture on the west coast and Anan, Tokushima Prefecture on the east coast. Northern parts, including Matsuyama, Takamatsu, and Tokushima, and central mountainous areas of Shikoku District were occupied only by *N. antennata* (Fig. 2. Note that black circles were converted
to double circles after the discovery of *N. viridula* in recent years).

Ohno and Nakamura (2007) searched for *N. viridula* in Matsuyama and Takamatsu in 2005, but they failed to find it. According to annual reports on light trap catches of pest insects in Ehime Prefecture, *N. antennata* has been trapped on many occasions in various localities up to the present, but *N. viridula* has been captured since 2004 in light traps in Matsuyama and Ainan, Ehime Prefecture. In 2007, it was trapped in Saijo, Imabari, and Masaki, Ehime Prefecture. We also confirmed the existence of *N. viridula* in Tokushima and Kamojima, Tokushima Prefecture by examining *N. viridula* specimens with labels indicating that they had been collected in 2007. In August 2008, we collected four *N. viridula* and five *N. antennata* from eggplants in Ayauta, Kagawa Prefecture.

**Chugoku District**

Prior to our field surveys in Chugoku District, *N. viridula* was collected in 1999 from Ohchi, Kawamoto, and Sakurae, Shimane Prefecture and Miyoshi and Yoshida, Hiroshima Prefecture (Nakamura et al., 2001), and in 2005 from Hinase, Ushimado, and Kojima, Okayama Prefecture (Ohno and Nakamura, 2007) (Fig. 3). From July to August 2007, 12 adults of *Nezara* were caught in a light trap in Akaiwa City, Okayama Prefecture, but they were all identified as *N. antennata* (Fusao Nakasuji and Kazuya Nagai, 2007, personal communication).

In 2007, we found both *N. viridula* and *N. antennata* in many localities in Yamaguchi Prefecture, including Hagi and Nagato along the coast on the Sea of Japan side where winter is warmer than in localities along the Seto Inland Sea coast (Table 1; Fig. 3; Japan Meteorological Agency, 2002, 2008). In northern parts of Shimane Prefecture, we found *N. viridula* in Goutsu, Ohda, and Unnan but not in Matsue, Izumo, and Hikawa (Table 1; Fig. 3). We also confirmed the absence of *N. viridula* from northern parts of Shimane Prefecture by referring to light trap catch data in Izumo from 1979 to

### Table 1. Relative abundance of *N. viridula* and *N. antennata* at various localities in Chugoku District and Hyogo Prefecture, Japan. Field data and light trap catches are combined

<table>
<thead>
<tr>
<th>Prefecturea</th>
<th>Localitya</th>
<th>Month &amp; Year</th>
<th><em>N. viridula</em> (%)</th>
<th><em>N. antennata</em> (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyogo</td>
<td>Sanda City</td>
<td>Sep. 2007</td>
<td>0 ( 0 )</td>
<td>12 (100)</td>
<td>12</td>
</tr>
<tr>
<td>Tottori</td>
<td>Iwami Town</td>
<td>Oct. 2007</td>
<td>0 ( 0 )</td>
<td>3 (100)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td><em>Ibid.</em></td>
<td>May–Aug. 2008</td>
<td>0 ( 0 )</td>
<td>16 (100)</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Tottori City</td>
<td>July–Aug. 2008</td>
<td>0 ( 0 )</td>
<td>3 (100)</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Hiedu Village</td>
<td>Oct. 2007</td>
<td>0 ( 0 )</td>
<td>24 (100)</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td><em>Ibid.</em></td>
<td>Aug. 2008</td>
<td>0 ( 0 )</td>
<td>8 (100)</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Hokuei Town</td>
<td>Oct. 2007</td>
<td>0 ( 0 )</td>
<td>2 (100)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td><em>Ibid.</em></td>
<td>July–Aug. 2008</td>
<td>0 ( 0 )</td>
<td>25 (100)</td>
<td>25</td>
</tr>
</tbody>
</table>

| Shimane    | Matsue City| Oct. 2007  | 0 ( 0 )      | 16 (100)      | 16 |
|           | Hikawa Town| Oct. 2007  | 0 ( 0 )      | 3 (100)       | 3  |
|           | Izumo City | Oct. 2007  | 0 ( 0 )      | 5 (100)       | 5  |
|           | Unnan City | Oct. 2007  | 1 (2.0)      | 49 (98.0)     | 50 |
|           | Ohda City  | Oct. 2007  | 3 (30.0)     | 7 (70.0)      | 10 |
|           | Goutsu City| Oct. 2007  | 27 (28.7)    | 67 (71.3)     | 94 |

| Yamaguchi  | Nagato City| Sep. 2007 | 3 ( 5.4 )    | 53 (94.6)     | 56 |
|           | Hagi City  | Aug. 2007 | 1 ( 3.1 )    | 31 (96.9)     | 32 |
|           | Yamaguchi City| Sep.–Oct. 2007| 44 (42.7)    | 59 (57.3)     | 103 |
|           | Iwakuni City| Sep. 2007 | 17 (70.8)    | 7 (29.2)      | 24 |
|           | Ube City   | Aug.–Sep. 2007| 32 (88.9)    | 4 (11.1)      | 36 |
|           | Shimonoseki City| Sep.–Oct. 2007| 133 (79.6)   | 34 (20.4)     | 167 |
|           | Hofu City  | Sep.–Oct. 2007| 106 (82.8)   | 22 (17.2)     | 128 |

*a Prefectures and localities within each prefecture are arranged from north to south.*

Reference:

Reference:
2008, although *N. antennata* has been caught almost every year (Table 2). In Tottori Prefecture (northeast of Shimane Prefecture), no *N. viridula* adults were caught in 2007 and 2008 in light traps set in various places in the prefecture (Table 1). Similarly, we could not find any *N. viridula* adults and larvae in 2007 in soybean and cornfields in Sanda, Hyogo Prefecture (Table 1).

The present data roughly indicate that there was a tendency for the relative abundance of *N. viridula* to *N. antennata* to be higher in southern localities than in northern localities.

Monthly mean temperature for January 2008 fell below 5°C in Yamaguchi City and in northeastern parts of Shimane Prefecture where we had found *N. viridula* in October 2007. In Yamaguchi, we collected an overwintered male *N. viridula* on 22 April 2008 from a cultivar of broccoli, “Hanakkori” in Japanese, *Brassica rapa* L.×*B. oleracea* L. (Brassicaceae). In September 2008, we collected 64 *N. viridula* adults from a rice field in Yamaguchi City. In northeastern parts of Shimane Prefecture, however, *N. viridula* was not collected either in light traps or from fields from April to July 2008.

**Changes in monthly mean temperatures for January**

Monthly mean temperatures for January fluctuated each year, resulting in changes of areas where *N. viridula* can overwinter successfully and persist continuously (Fig. 4). In 1961, there were almost no places in Chugoku District and the northern parts of Shikoku District where monthly mean temperatures for January exceeded 5°C. In 2000, the areas expanded along the coastline of Shikoku District and southwestern Honshu owing to the warm winter temperature in that year, while winter 2001 was much colder. Thus, monthly mean temperatures for January have been fluctuating each year, hence the areas where *N. viridula* can overwinter successfully have been becoming broader or narrower. In recent years, however, the whole of the coastline in Shikoku District has been included in the potential distribution areas of *N. viridula*. The monthly mean temperature for January 2008 was 6.0°C in Matsuyama and 5.7°C in Takamatsu.
(Japan Meteorological Agency, 2008). The coastline on the Japanese Sea side in Chugoku District was not always included in *N. viridula* potential distribution areas even after 2000. The monthly mean temperature for January 2008 fell below 5°C in many places of Chugoku District where *N. viridula* had been found previously (Fig. 3).

**DISCUSSION**

**Northward expansion of distribution range by *N. viridula***

Sequence and RAPD results both support the African origin of *N. viridula*, followed by dispersal to Asia and, more recently, expansion to Europe and America (Kavar et al., 2006). In Japan, *N. viridula* was recorded first in 1874 (location not given) and then in 1879 in Nagasaki Prefecture, Kyushu (Hasegawa, 1954); thereafter, no reliable collection record of *N. viridula* was available in Japan until the 1950s, possibly due to morphological confusion with *N. antennata*. In 1952, its occurrence was confirmed in Kagoshima Prefecture, Kyushu and then in southern Shikoku and Wakayama Prefecture, Honshu (Hasegawa, 1954; Yukawa et al., 2007). In contrast, *N. antennata* is an Asian species, widely distributed in Japan from Okinawa to Hokkaido, Korea, China, and southeastern Asian countries (e.g., Hayashi, 2002).

*N. viridula* did not exist in northern parts of Shikoku District in 1972–1973, but it is now distributed widely in Shikoku District, except mountainous areas (Fig. 2). The monthly mean temperature for January in northern Shikoku was warm enough after 2000 for *N. viridula* to overwinter with a high survival rate (Fig. 4) (Japan Meteorological Agency, 2008). In Okayama Prefecture, *N. viridula* was found in 2005 in 3 of 6 localities surveyed by Ohno and Nakamura (2007), although not in Akaiwa in 2007 (Nakasuji and Nagai, 2007, personal communication). The finding of *N. viridula* in Okayama Prefecture, north of Shikoku District, supports its existence in northern parts of Shikoku District.

In Yamaguchi Prefecture, there were no reliable collection records of *N. viridula* before 2004 (Yukawa et al., 2007). Takahashi and Mochida (1992) erroneously included Yamaguchi Prefecture in the distribution range of *N. viridula* by referring to Kawasawa et al. (1973), although this prefecture was not included; therefore, the present data are the first reliable collection record of *N. viridula* in Yamaguchi Prefecture. Although there was no earlier distribution record of *N. viridula* in northern parts of Shimane Prefecture (Table 2), it was collected there in 1999 (Nakamura et al., 2001) and its existence was reconfirmed by our 2007 survey (Fig. 3).

Thus, the differences between the previous and recent distribution patterns of *N. viridula* in Shikoku and Chugoku Districts clearly indicates that *N. viridula* has expanded its distribution range northward in recent years, possibly due to global warming, as has been noted in the Kii Peninsula and Kyushu District (Yukawa et al., 2007; Tougou et al., 2009).

It is remarkable that most areas along the southeastern seacoast in Shikoku District were already occupied only by *N. viridula* at the time of the 1972–1973 surveys. This means that *N. antennata* has been replaced by *N. viridula* by interspecific mating between the two *Nezara* bugs, as has been noted in the Kii Peninsula (Kiritani et al., 1963) and in Kyushu District (Yukawa et al., 2007). In Chugoku District, no areas are occupied by only *N. viridula*, suggesting the recent invasion of this district by *N. viridula*; however, the higher relative abundance of *N. viridula* to *N. antennata* in southern localities in Yamaguchi Prefecture (Table 1) may indicate that *N. viridula* is now replacing *N. antennata* in those areas.

**Fluctuations in the northern limit of *N. viridula***

The northern limit of *N. viridula* is not always fixed, moving northward and southward, possibly depending on the winter temperature. Kiritani et al. (1966) and Kiritani (1971) proposed a regression line, $Y = -16.45X + 147.08$ ($R^2=0.6127$, $p<0.0001$), between the mortality of *N. viridula* ($Y$) and the mean temperature for January ($X$). This suggests that every 1°C rise would result in a decrease in winter mortality of about 16.5% in *N. viridula*, provided that $X$ remains from 3 to 7°C (Kiritani, 2006, 2007); therefore, winter mortality would become about 65% at 5°C, which is the northern range limit of *N. viridula*. We collected *N. viridula* from northern parts of Shimane Prefecture in October 2007 (Fig. 3), but did not found it there again in the field survey and light trap catches from April to July 2008. This was probably due to the relatively low monthly mean temperature for January.
N. viridula has not been found in Tottori Prefecture (Table 1), the most northerly part of Shimane Prefecture (Izumo and north of Izumo) (Table 2), and Sanda, Hyogo Prefecture (Fig. 3), where the monthly mean temperature for January 2008 was below 5°C (Figs. 3 and 4). These records of absence are important for documenting future range expansion by N. viridula.

Because monthly mean temperatures for January fluctuate each year, areas where N. viridula can overwinter successfully become broader or narrower, as shown in Fig. 4. Thus, the northern limit of the N. viridula distribution range moved northwards in milder winters, but retracted in colder winters. In addition, interspecific mating of rare N. viridula females with N. antennata males may cause the southward retreat of the northern limit of N. viridula when its population density remained low under relatively cold conditions.

Tougou et al. (2009) pointed out that N. viridula was found mostly close to localities where the mean number of cold days (with the mean temperature below +5°C) did not exceed 26 in January to February and where the mean annual lowest temperature did not drop below −3.0°C. These additional temperature conditions are worth considering when determining the northern range limit of N. viridula, but cannot be used directly to explain the annual fluctuation of the northern range limit because these temperature conditions are derived from the mean data in 1960–1969 and 1998–2007.

The maps (Fig. 4) show the possibility that N. viridula will expand its distribution range soon to the Kanto District, Honshu when the monthly mean temperature for January exceeds 5°C continuously for several years.

N. viridula is known as an economically important bug responsible for empty or pecky rice grains. Once it has established newly invaded areas, rice production is seriously affected in addition to the loss already caused by other hemipteran bugs, such as Trigonotylus caelestialium (Kirkaldy) (Miridae), Leptocorisa chinensis Dallas (Alydidae) and others. The prediction of range expansion, early detection, and early treatment of N. viridula are required.

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