Neotrop Entomol (2016) 45:619–628
DOI 10.1007/s13744-016-0446-2

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What Happened to *Nezara viridula* (L.) in the Americas? Possible Reasons to Explain Populations Decline

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Keywords

Heteroptera, Pentatomidae, southern green stink bug, zoogeographical regions, population abundance

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Edited by Jorge B Torres – UFRPE

Received 28 June 2016 and accepted 9 September 2016
Published online: 1 November 2016

Abstract

Once abundant in the Americas, the southern green stink bug *Nezara viridula* (L.) has gradually declined in numbers. Until the 1990s, it was considered the main pest of major crops such as soybean, *Glycine max* (L.) Merrill, particularly in southern Brazil and southern USA, as well as Argentina, Uruguay, and other countries. In the past 15+ years, a dramatic population decrease was observed to the point of now being considered a secondary pest in these referred countries. In this article, we list and discuss possible reasons which explain the decline in *N. viridula* population in the Americas. These factors include the following: (1) the steady increase of herbicides used in no-tillage/multiple cropping systems affecting potential hosts such as weeds in crop fields and nearby natural vegetation; (2) the change in cultivation systems, mostly in the Neotropics, favoring other species more adapted to exploit crops in modern day agriculture; (3) competition among several species of stink bugs that colonize major crops; (4) the growing impact of several species of egg parasitoids, some of them laboratory reared and released in crop fields, and other natural enemies (parasitoids and predators); and (5) the impact of global climate change affecting its distribution and biology.

Introduction

The cosmopolitan and highly polyphagous southern green stink bug, *Nezara viridula* (L.) (Hemiptera: Heteroptera: Pentatomidae), has been recorded in most zoogeographical regions of the world including Africa, Americas, Asia, and Europe (Lethierry & Severin 1893, Todd 1989). Its distribution was mapped in 1953 (Anonymous 1953) and updated in 1970 (Anonymous 1970, Dewitt & Godfrey 1972) and in 1980 (Todd & Herzog 1980) (Fig 1a). Since that time, *N. viridula* has spread in many regions of the world, including expansions in the Neotropical and Afrotropical regions following the spread of agriculture; a similar phenomenon has occurred in the Nearctic and Palearctic regions, possibly influenced in these last two regions by global climate change (Fig 1b).

In spite of the appearance of *N. viridula* in new areas in recent years, the decrease in its populations in some earlier known areas of occurrence, such as in the Neotropical and Nearctic regions, has also been observed. These observations have led us to examine in detail if this is really occurring or not. Accordingly, we decided to make an extensive literature survey for the past 50 years of all records regarding the occurrence of *N. viridula* on different crops (mostly soybean) in the Americas, separating the Nearctic region, including only the USA where *N. viridula* occurs, from the Neotropical region. We ranked the position of *N. viridula* (from most abundant to less abundant) as first, second, third, or greater than that, and absent, in relation to other common associated species of pentatomids found in different crops.

To test our hypothesis that the relative abundance of *N. viridula* is in decline, we separated the data from the literature into two time periods: Period 1 covered the years 1969 to 1999, and period 2 covered the years 2000 to 2015.

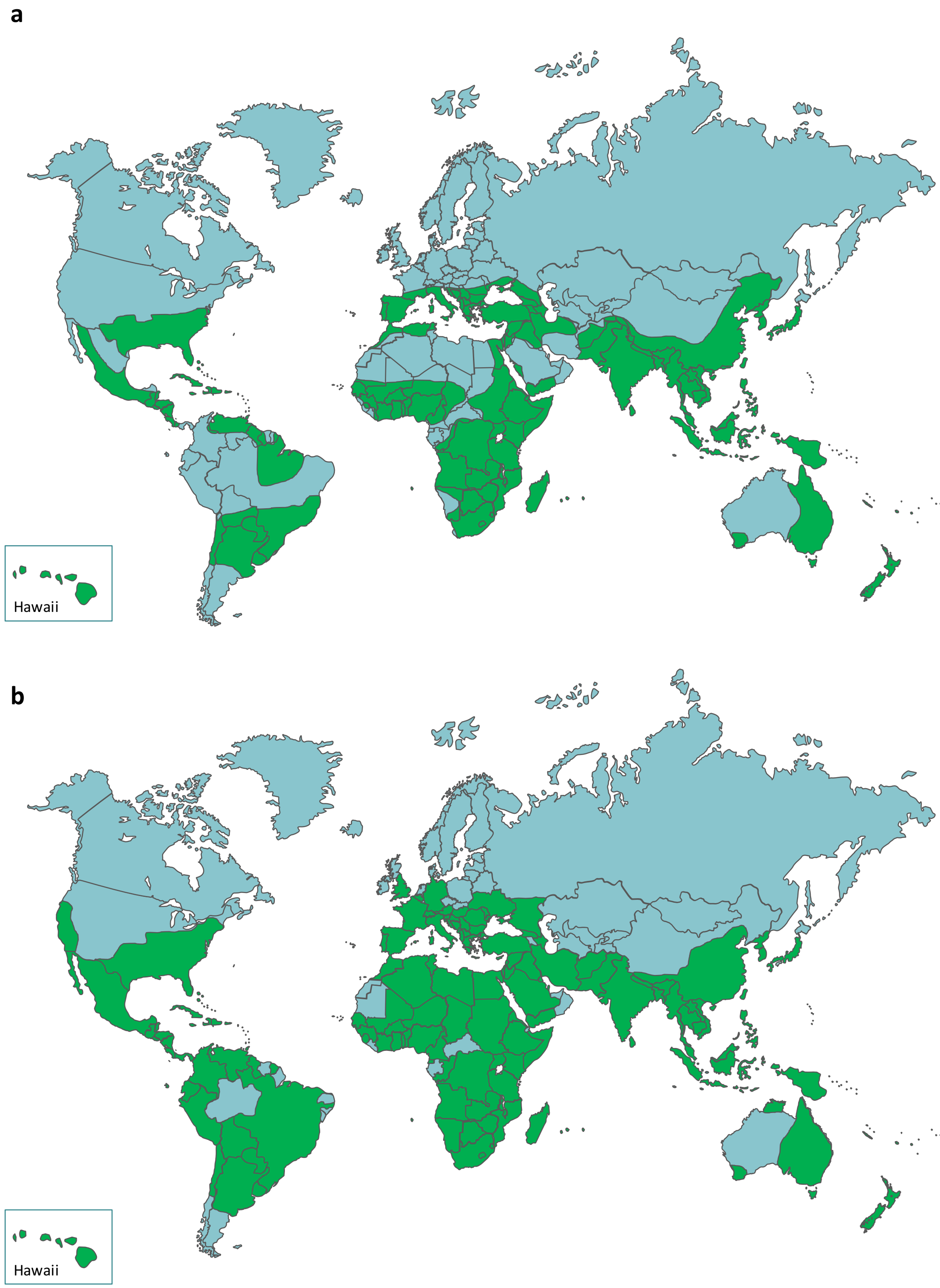

Fig 1 World distributional map of *Nezara viridula* according to the Commonwealth Institute of Entomology updated by Todd & Herzog (1980) (a) and updated (2016) with records from selected literature (Panizzi & Slansky 1985, Waterhouse & Norris 1987, Moscardi 1993, Clarke 1992, Colazza & Bin 1995, Haseeb & Kairo 2006, Salisbury *et al* 2009, Anonymous 2016) (b).

These two time periods were separated based on the estimated time taken by factors that have acted to explain *N. viridula* decline in abundance in the Americas. These factors primarily influenced populations during the 1980–1990 decades, and their effects accumulated with time; therefore, we considered the year 1999 as a good dividing time point.

These factors include the dramatic increase in use of herbicides in cropping systems to manage weeds (eliminating potential *N. viridula* hosts) and to anticipate crop maturation (burn down), the massive adoption of the no-tillage cultivation system and multiple cropping system in the Neotropics favoring more adapted pest species, the inter-specific competition among pentatomids, the increased impact of egg parasitoids and other natural enemies, and the global climate change effect (see following discussion).

Relative Abundance of *N. viridula* in the Nearctic Region (USA)

N. viridula in the Nearctic region (USA) has been recorded mostly in the continental south, southeast, and northeast states and in the west in California, and in Hawaii, totalizing 21 states (Fig 2). *Nezara viridula* probably occurs in other states as well, but its presence in low numbers might have passed unnoticed.

We were able to find 71 records published in 1974–2013 of *N. viridula* occurrence in different crops, mostly soybean; from these records, we were able to rank their relative abundance compared with other species of pentatomids commonly found in the same crop (Table 1 with references in supplemental material in the online version).

The records obtained for the first time period examined (1974 to 1999) indicated that in over 80% of the cases, *N. viridula* was ranked as the most abundant stink bug (Fig 3a). However, when the records were analyzed for the second time period (2000 to 2013), the relative abundance of *N. viridula* changed dramatically; in only 12% of the cases, *N. viridula* was ranked first, and in the majority of the cases (32%), *N. viridula* was ranked third+ or its occurrence was not mentioned (Fig 3b).

To further demonstrate the decrease in relative abundance of *N. viridula* in the Nearctic region (USA), we calculated its percent abundance in different decades; to accomplish this, we selected literature references which had or allowed calculation of percent abundance values. The data analysis indicated a gradual decrease along the decades analyzed; *N. viridula* composed over 50% of the total stink bugs sampled in the 1970s and 1980s and 49% in the 1990s; on the following two decades (2000/2009 and 2010/2013), these values drastically dropped to 21% in the first decade, down to 6% in the last 5 years (Fig 4a). This data analysis clearly indicates that in the past 15 years, the decrease in abundance has accentuated, with *N. viridula* losing its former pest status in the USA.

Relative Abundance of *N. viridula* in the Neotropical Region

As opposed to the Nearctic region, where *N. viridula* occurs only in the USA, in the Neotropical region, *N. viridula* is widely distributed. It is present in the majority of the countries (except in the southern parts of Argentina and Chile, in the Amazon Basin, a few states in the north/northeast of Brazil, and in Suriname in northern South America); it is also well distributed in Central America with records of its occurrence for all countries and most islands (Fig 5). The expansion of agriculture in the Neotropics, particularly of its preferred host,

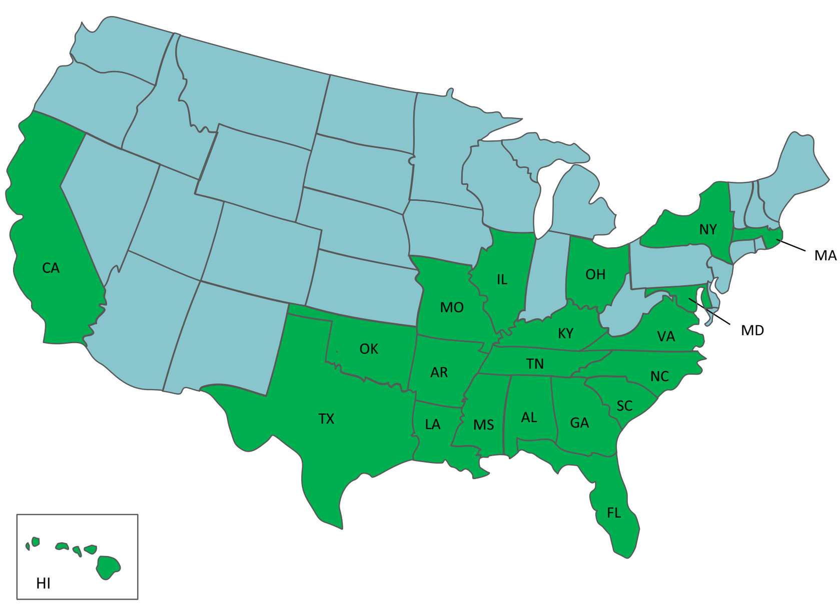

Fig 2 Geographical distribution of *Nezara viridula* in the Nearctic region—different states of the continental USA and in Hawaii (based on the following selected sources: Jones & Sullivan 1978, 1982, 1984, Killian & Meyer 1984, Troxclair & Boethel 1984, Jones & Cherry 1986, Hoffmann *et al* 1987, Jones & Caprio 1992, McPherson *et al* 1993, Baur *et al* 2000, Snodgrass *et al* 2005, Haseeb & Kairo 2006, Anonymous 2016).

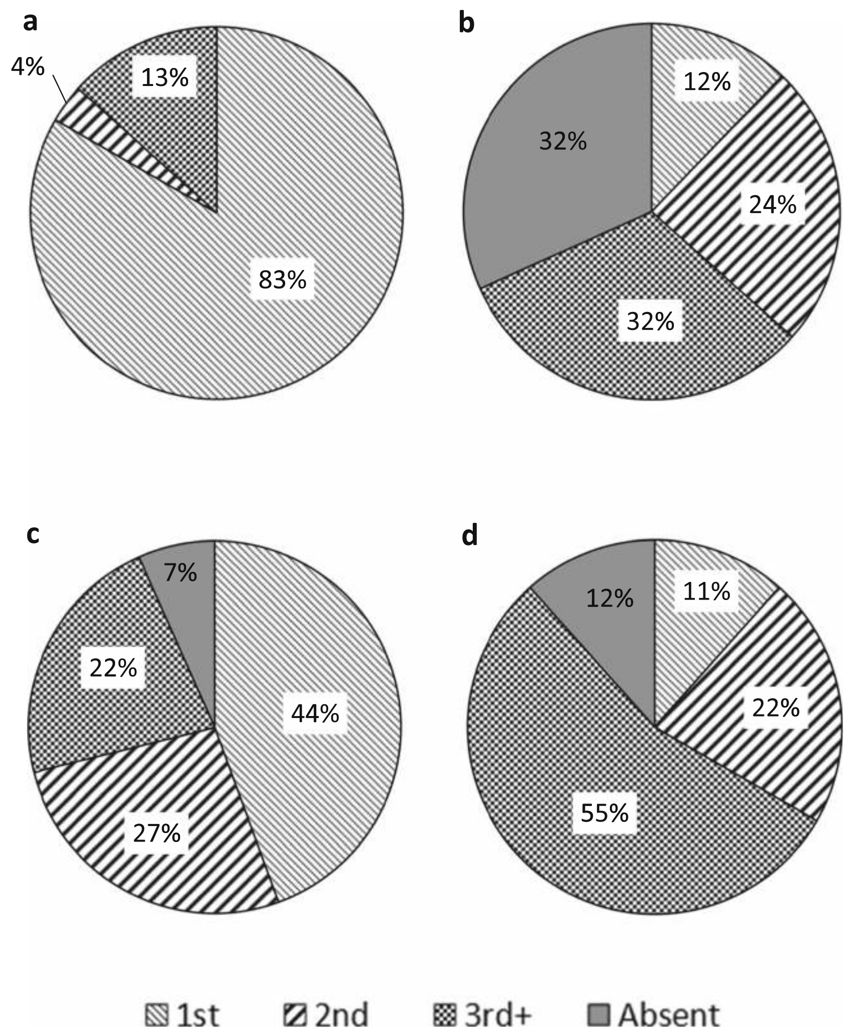

Fig 3 Abundance of *Nezara viridula* in the Nearctic region (USA) from 1974 to 1999 (a) and from 2000 to 2013 (b) and in the Neotropical region from 1969 to 1999 (c) and from 2000 to 2015 (d) on different plants (data based on literature survey from Tables 1 and 2, supplemental material in the online version, considering its rank as first, second, third+ most abundant species compared to other species of pentatomids referred, and absent).

soybean, has resulted in its wide distribution in Brazil toward the central-west and northeast areas of the country (Panizzi & Corrêa-Ferreira 1997, Panizzi 2002).

A survey from 1969 to 2015 revealed 114 literature records of the occurrence or not of *N. viridula* on different host plants (except for one case of captures using light traps on wild vegetation). These records were obtained mostly from the soybean crop, in Brazil, Argentina, and Uruguay; the abundance of *N. viridula* was ranked in relation to other species of pentatomids (Table 2 and references in supplemental material in the online version).

During the first period (1969 to 1999) considering 45 literature records, the majority (44%) indicated that *N. viridula* was the most abundant stink bug; in 7% of the cases, there was no reference to *N. viridula* (considered as absent) (Fig 3c). However, when the remaining 69 records obtained from 2000 to 2015 were analyzed, a sharp decrease in relative abundance of *N. viridula* was observed; in only 11% of the cases was the bug ranked as the most abundant; and, in 12% of the cases, was not referred as being present (Fig 3d).

Similar to the Nearctic region, the relative abundance of *N. viridula* gradually decreased from decade to decade. The data analysis based on literature references demonstrated that its relative abundance dropped from 41% at the first decade examined (1970/1979) to 12% in the last (2010/2015) (Fig 4b). The analysis of this extensive set of data from the literature clearly demonstrates that *N. viridula* in the last 15+ years is becoming less abundant in the area of its earlier occurrence in the Neotropical region.

Reasons for the Decline of *Nezara viridula* in the Americas

Our suspicions that *N. viridula* abundance has declined in the Americas were clearly confirmed by the analysis of the extensive set of data obtained from the literature in the past almost 50 years. We have selected the main reasons believed to cause this reduction and discuss their possible implications to this phenomenon as follows.

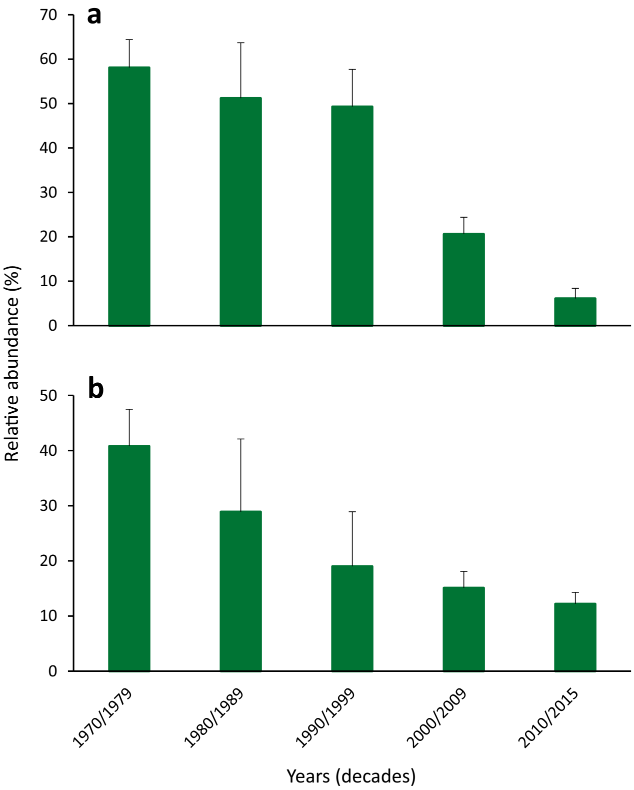

Fig 4 Mean (±SEM) abundance of *Nezara viridula* in the Nearctic region (USA) (a) and in the Neotropical region (b) at different decades from 1970 to 2015 (data calculated from information obtained from the following sources from Table 1: 1, 2, 7, 9, 11, 15, 16, 18, 20–24, 26–30, and 32–37 and from Table 2: 1, 2, 5, 6, 9–11, 14, 16, 18, 21–25, 28, 31, 32, 34, 35, 37, 39–46, 49–58, 60, 61, and 63–72 in supplemental material in the online version, respectively).

Fig 5 Geographical distribution of *Nezara viridula* in the Neotropical region (based on the following selected sources: Costa & Link 1974, Corrêa *et al* 1977, Vicentini & Jimenez 1977, Prado *et al* 1982, Panizzi & Slansky 1985, Ramiro *et al* 1986, Meglič *et al* 2001, Panizzi 2002, Pavlovčič *et al* 2008, Anonymous 2016). Brazil (*BR*), Bolivia (*BO*), Paraguay (*PA*), Argentina (*AR*), Chile (*CH*), Uruguay (*UR*), Peru (*PE*), Ecuador (*EC*), Colombia (*CO*), Venezuela (*VE*), Guyana (*GU*), French Guiana (*FG*), Galapagos Islands (*GI*), Panama (*PAN*), Costa Rica (*CR*), Nicaragua (*NI*), Honduras (*HO*), El Salvador (*ES*), Guatemala (*GUA*), Belize (*BE*), Mexico (*MX*), Bahamas (*BA*), Cuba (*CU*), Jamaica (*JA*), Haiti (*HA*), Dominican Republic (*DR*), Puerto Rico (*PR*), Trinidad and Tobago (*TT*), Anguilla (*AN*), Antigua and Barbuda (*AB*), Barbados (*BAR*), British Virgin Island (*BV*), Dominica (*DO*), Grenada (*GR*), Montserrat (*MO*), St. Kitts and Nevis (*SKN*), St. Lucia (*SL*), St. Vincent and the Grenadines (*SVG*), US Virgin Islands (*USV*), French West Indies (*FWI*).

The use of herbicides in cropping systems

With the massive adoption of the no-tillage cultivation system and with the introduction of multiple cropping systems, particularly in the Neotropics, the management of weed plants has become a critical issue. The general use of herbicides to eliminate weeds in pre-seeding or post-seeding or to eliminate weeds close to the crop maturation, and to burn down crops to shorten their cycle to allow multiple cropping, has dramatically increased the worldwide agricultural application of these chemicals. For example, in Brazil alone, the amount of herbicides sold annually increased from 151,100 t in 1998 to 497,664 t in 2015 (source: www.sindiveg.org.br), annually increasing steadily during this time period (Fig 6). This massive use of herbicides has led to the drastic reduction and even disappearance of several species of weed plants, many of them hosts on which *N. viridula* is able to reproduce or associated plants on which it feeds and finds shelter without reproducing (Panizzi 1997).

It has long been known that *N. viridula* is highly polyphagous. Hoffman (1935) listed 115 plant species from 32 families as food plants of the bug. In a recent survey in the Neotropics, Smaniotto & Panizzi (2015) found 70 species of plants from 19 families, many of those considered weed plants, on which *N. viridula* was observed feeding and/or reproducing, confirming its high polyphagy. Undoubtedly,

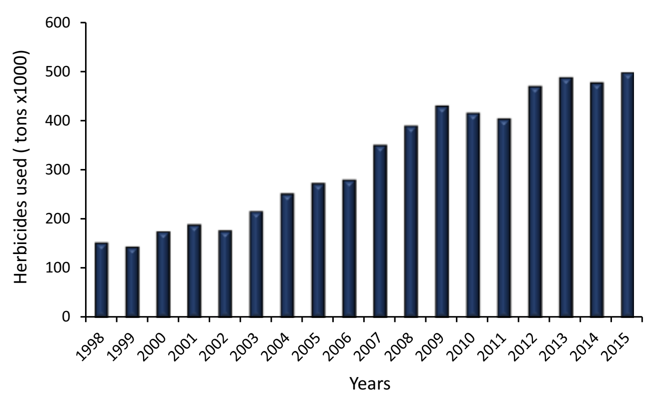

Fig 6 Total amounts of herbicides used in agriculture annually from 1998 to 2015 in Brazil (source: www.sindiveg.org.br).

elimination of weed plants in crop fields and border areas has adversely affected survival of *N. viridula*. In the Neotropics, *N. viridula* is known to complete several generations (ca. three per year) in sequence on cultivated plants, and additional generations are completed on wild plants (Panizzi 1997). Because of its extreme polyphagy, we believe that the wide elimination of several plant species by herbicides greatly affects *N. viridula* in comparison to the other species of stink bugs, which are less polyphagous and better adapted to survive in the absence of food plants [e.g., *Euschistus heros* (F.)].

No-tillage cultivation and multiple cropping systems

A general change in the entomofauna inhabiting cropping systems has been observed with the general adoption of the no-tillage cultivation system and with the introduction of sequential cultivation (multiple cropping), in particular in the Neotropical region (Panizzi & Corrêa-Ferreira 1997). Under no-tillage agriculture, residues of the former crop provide shelter for many insects, as well as fallen seeds for food. This combination of shelter plus food had a tremendous impact, not only on soil inhabiting insects but also on those that pass part of their life on the soil. Among these are several species of pentatomids, such as the Neotropical brown stink bug, *E. heros*, and the green belly stink bugs, *Dichelops furcatus* (F.) and *Dichelops melacanthus* (Dallas) (Panizzi 2015). Another species, the redbanded stink bug, *Piezodorus guildinii* (Westwood), is known to overwinter on the ground underneath eucalyptus litter where they remain protected until the next spring (Zerbino *et al* 2015).

N. viridula shelters during unfavorable conditions under litter, bark, or objects that offer protection (refs. in Todd 1989). However, as opposed to the previously mentioned stink bug species, *N. viridula* does not take advantage of residues left on the ground under the no-tillage regime. Apparently, after crop harvest, this bug leaves the area looking for alternate hosts or shelters elsewhere; this might be due to its extreme polyphagous habit. Moreover, in southern Brazil, *N. viridula* evidently does not store lipids as an energy source to survive unfavorable times as much as does *E. heros* that spends several months underneath debris (Panizzi & Hirose 1995). The latter species and others (*D. furcatus* and *D. melacanthus*) that stay on the ground take advantage of this habit and feed on seedlings of cultivated plants that are grown in sequence (Quintela *et al* 2006). This adds additional food resources in their life history. In contrast to *N. viridula*, the adaptations observed for other endemic stink bugs have contributed to their relative superiority nowadays.

Stink bug inter-specific competition

Despite their polyphagy, considering their similar feeding preferences, several species of pentatomids tend to coexist on the same food plant species. This is more likely to occur when food is abundant as in the case of cultivated plants. As populations grow, inter-specific competition starts to exert pressure favoring those species that are better adapted.

To compare the abundance of co-existing populations of different species of stink bugs, we selected literature references that allowed us to calculate the relative abundance of different species. This was done for each decade from 1970 to 2015. The mean (±SEM) of the relative abundance of *N. viridula* in each decade was compared with the abundance of other species of stink bugs: in the Nearctic region: *Chinavia hilaris* (Say), *Euschistus servus* (Say), *Euschistus obscurus* (Palisot), *Euschistus quadrator* Rolston, *Euschistus tristigmus* (Say), *Oebalus pugnax* (F.), *Thyanta custator* (F.), *Thyanta custator acerra* McAtee, and *P. guildinii*; in the Neotropical region: *E. heros*, *D. furcatus*, *D. melacanthus*, *Edessa meditabunda* (F.), and *P. guildinii*.

For both regions, the relative abundance of *N. viridula* has gradually decreased, while the abundance of competing species of stink bugs has increased. In the Nearctic region, *N. viridula* was dominant in the 1970s; in the two subsequent decades, its population was similar to that of the other species, and in the years 2000 to 2015, *N. viridula* has sharply decreased in abundance, while populations of another species have increased (Fig 7a). The data from the literature survey revealed that, as *N. viridula* populations mitigated, populations particularly of the brown stink bug complex (including four species of *Euschistus*) have increased.

In the Neotropics, a similar situation was observed. *Nezara viridula* populations decreased from decade to decade, while the populations of another species of pentatomids increased (Fig 7b). The Neotropical brown stink bug, *E. heros*, was rare in the 1970s (Panizzi *et al* 1977), but today is the most abundant stink bug pest of soybean and other major crops in Brazil. *Euschistus heros* completes four generations per year in northern Paraná state, Brazil (Panizzi 1997), overwintering under dead leaves during the mild winter (Panizzi & Niva 1994). In the new scenario of no-tillage/multiple cropping, it has dramatically increased, expanding its range into most of the Brazilian territory and even invading Argentina (Saluso *et al* 2011). Recent studies conducted in the field indicated that *E. heros* is a superior competitor compared to *P. guildinii* in soybean (Tuelher *et al* 2016). Moreover, *E. heros* is considered more tolerant to insecticides than *P. guildinii* or *N. viridula* (Willrich *et al* 2003, Snodgrass *et al* 2005), which likely contributes to the prevalence of *E. heros*. Therefore, these driven forces are believed to be causing the decline in *N. viridula* populations.

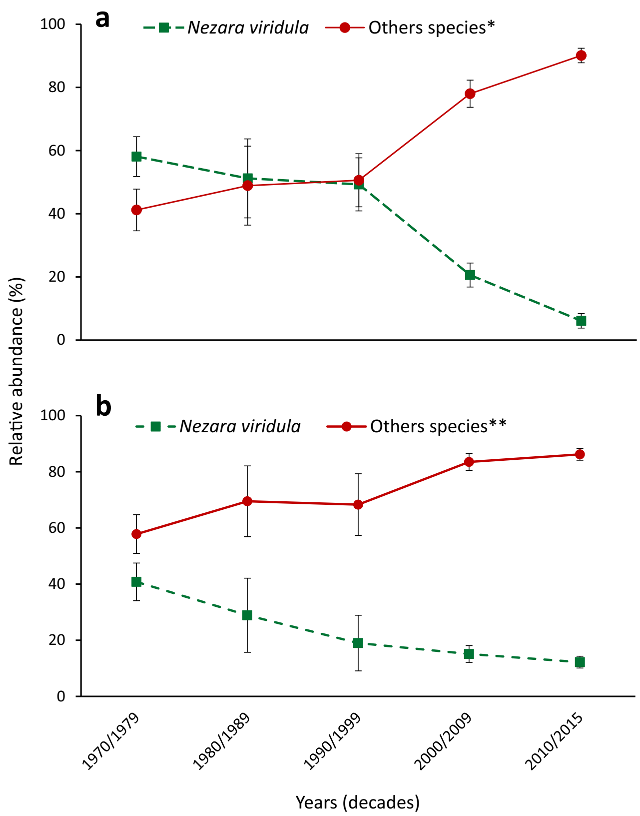

Fig 7 Mean (±SEM) relative abundance of *Nezara viridula* in relation to other species of stink bugs present on different plants in the Nearctic region (a) and in the Neotropical region (b) from 1970 to 2015 [data calculated from information obtained from the following sources from Table 1 (Nearctic region): 1, 2, 7, 9, 11, 15, 16, 18, 20–24, 26–30, and 32–37 and from Table 2 (Neotropical region): 1, 2, 5, 6, 9–11, 14, 16, 18, 21–25, 28, 31, 32, 34, 35, 37, 39–46, 49–58, 60, 61, and 63–72, in supplemental material in the online version, respectively]. Single asterisk refers to *Chinavia hilaris*, *Euschistus servus*, *Euschistus obscurus*, *Euschistus quadrator*, *Euschistus tristigmus*, *Oebalus pugnax*, *Thyanta custator*, *Thyanta custator acerra*, and *Piezodorus guildinii*; double asterisk refers to *Euschistus heros*, *Dichelops furcatus*, *Dichelops melacanthus*, *Edessa meditabunda*, and *Piezodorus guildinii*.

The impact of egg parasitoids and other natural enemies

The parasitoid, *Trissolcus basalis* (Wollaston), was first discovered parasitizing eggs of *N. viridula* in Brazil in the late 1970s (Corrêa-Ferreira 1980). Since that time, parasitism on *N. viridula* eggs increased annually, reaching as much as 80% of the total eggs collected from soybean fields in the 1990s (Corrêa-Ferreira 1993).

Among the several reasons to explain the increase on the incidence of parasitoids on the eggs of *N. viridula* in the Neotropics, two can be considered the most important: the field release of parasitoids artificially reared in the laboratory and the general mitigation in the use of insecticides observed in the late 1970s until the end of the 1990s, plus the use of more selective insecticides.

The field release of parasitoids reared in the laboratory had a tremendous impact on the biological control of *N. viridula*. Successful programs developed in Brazil (Corrêa-Ferreira 1993) and in Argentina (Liljesthröm *et al* 2013), for example, were fundamental in the augmentation of the parasitoid incidence decreasing the populations of *N. viridula* on its main host plant, soybean. A methodology to rear *N. viridula* in the laboratory to obtain and store egg masses, to expose them to the parasitoids in the laboratory, and to release them in the field was implemented successfully (Corrêa-Ferreira 1993); this surely help to enhance the biocontrol of *N. viridula*.

The implementation of IPM programs in the Neotropics in the 1970s and 1980s, with adoption of economic injury levels for major pests, substantially reduced the amount of insecticides in several crops; in Brazil on soybean, the amount of insecticide used was cut by half (Gazzoni 1994). In addition, in general, more selective insecticides and use of reduced dosages were promoted (Corso 1990), reducing the adverse effect on the egg parasitoids, such as *T. basalis*, and also on other natural enemies.

Nowadays, under the no-tillage/multiple cropping scenario, natural enemies may have had a greater impact on *N. viridula* survivorship and abundance than on other species of stink bugs. For example, tachinid flies that parasitize stink bug adults exhibited a much greater impact on *N. viridula* (30 to 100% parasitism), compared to that for *E. heros* (0 to 37%). Moreover, *N. viridula* adults were heavily parasitized (>90%) by tachinid flies during the mild winter (June to early September) in northern Paraná state, Brazil, where adults were congregated on few host plants; for *E. heros*, which were sheltered beneath dead leaves at this time, parasitism was virtually nil (Panizzi & Oliveira 1999).

Global climate change

Global climate change affecting arthropod range expansion, replacement of dominant species, seasonal phenology, and occurrence of potential pests has been extensively discussed in the literature (see Kiritani 2006 and references therein). For *N. viridula*, in particular, several studies have demonstrated that global climate change is affecting its biology. For example, Tougou *et al* (2009) reported that in the 1960s, the northern limit of *N. viridula* in Japan was in Wakayama Prefecture; ca. 40 years later (2006/2007), this northern limit had extended 85 km northward, with a mean rate of 19 km/decade. This is attributed to milder winter conditions, leading to greater survival of the overwintering bugs. Moreover, global climate change affects the control of diapause termination and post-diapause reproduction; this may carry a complex influence over time upon the life history and phenological parameters of *N. viridula*, as demonstrated through several studies conducted in Japan (Musolin & Numata 2003, Musolin *et al* 2007, 2010, Musolin 2012).

The impact of global climate change may also be speculated as dislodging *N. viridula* from its adapted annual phenology to cultivated crops and shelter reservoirs and affecting its biology. Its expansion into colder areas of the Nearctic and Palearctic regions, and even in the Neotropical region in Argentina, southward in the last years is a fact [compare *N. viridula* distribution up to the 1980s (Fig 1a) and up to 2009 (Fig 1b)]. The elevated temperature probably allows expansion of populations to new "warmer" areas, becoming established in these new habitats; however, this does not mean that its total population is increasing as we consider the decline in its abundance in the traditional areas of occurrence.

It is interesting that global climate change may have a double effect. For instance, global climate change allows *N. viridula* to expand and colonize new habitats as we previously discussed, while the alleviation of winter temperatures during the cooler months of the year, in particular in areas with mild winters, may result in greater pressure of natural enemies on *N. viridula* populations. For example, tachinid flies can parasitize 100% of *N. viridula* adults found concentrated on host plants during winter in the Neotropics (Panizzi & Oliveira 1999), and the warmer it gets, the more active these flies and other natural enemies are. Moreover, summer temperatures might be too high for *N. viridula* in the tropical regions.

Concluding Remarks

Based on the literature records surveyed from the Nearctic and Neotropical regions and on the personal observations of the first author carried in the Neotropics (Argentina, Brazil, and Uruguay), there is no doubt that the former main pentatomid pest, *N. viridula*, is decreasing in abundance and pest status in the Americas. We believe that the increased use of herbicides, the advent of no-tillage and multiple cropping, the inter-specific competition, the impact of natural enemies, and the global climate change are the main reasons causing this decline.

It is also worth mentioning the difficulty the several Brazilian entomologists are experiencing in keeping colonies of *N. viridula* in the laboratory. This has been a common complaint; the classical use of green bean pods plus unshelled raw peanuts seems not to work as well as it did in the past. In general, colonies start well, but after few generations, they collapse. Is it the Brazilian population of *N. viridula* that changed along the years or the food that might be recently contaminated with pesticides, or what? Surely, detailed studies are needed to explain these observations.

In conclusion, the decline of *N. viridula* in the Americas is a fact. However, time will certainly show if this decline is permanent or if populations will rebound. And, as we learn more about *N. viridula* biology, we should be able to better explain this phenomenon.

Acknowledgments We thank Jeffrey Aldrich and two anonymous reviewers for critically reading the manuscript and improving its readability. This manuscript is a result of many informal discussions A. R. P. has had in recent years with several researches working with *Nezara viridula*, particularly in the Neotropics to whom we thank. Among them, Beatriz S. Corrêa-Ferreira, Daniel R. Sosa-Gomez, Miguel Borges, Raul Laumann, Lucia Vivan, Crébio Ávila, Jocélia Grazia, and Paulo R.V. S. Pereira in Brazil; Jorge Aragon (deceased), Fernando Flores, Adriana Saluso, and Raul Vicentini in Argentina; and Maria Stella Zerbino and Enrique Castiglione in Uruguay. This study was partially supported by a National Council of Research and Technology of Brazil (CNPq) grant 471517/2012-7 to A. R. P. and by a scholarship from CAPES (Ministry of Education) of Brazil to T. L. Approved by the Publication Committee of the Embrapa Wheat, Passo Fundo, RS, Brazil under number 5376/2016.

Electronic supplementary material The online version of this article (doi:10.1007/s13744-016-0446-2) contains supplementary material, which is available to authorized users.

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