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REVIEW ARTICLE

Life history studies of stink bugs: much-needed research to support their conservation biological control

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Abstract In this article, we present and discuss the importance of life history information of four species of stink bugs (Heteroptera: Pentatomidae) of the neotropics, pests of major commodities, as basic information necessary for development of improved programs of conservation biological control. This information is from cultivated areas in two ranges in southern latitudes: 10–23° S of the sub-tropical warm area, for *Euschistus heros* (F.) and *Diceraeus melacanthus* (Dallas), and 23–36° S of the sub-temperate area, for *Piezodorus guildinii* (Westwood) and *Nezara viridula* (L.). We present the life histories of the stink bugs, showing their relative abundances on crops and wild vegetation and the number of generations completed per year. We describe the main groups of natural enemies and suggest how their roles might be enhanced to reduce the abundance of the pests. We discuss a variety of plants affecting stink bugs and their natural enemies, including primary host plants and associated plants. We proposed a theoretical "ideal" landscape with improved spatial and temporal distributions of host and non-host plants in cultivated and non-cultivated parts of agricultural systems. We suggest some future steps that need to be taken to make this "ideal" landscape a reality, mitigating the harmful effects of stink bugs as pests, enhancing their natural enemies, and promoting conservation biological control.

Keywords Pentatomidae · Pests · Natural enemies · Biocontrol

Introduction

Stink bugs (Hemiptera: Heteroptera: Pentatomidae) have long been known as significant pests of several plants of economic importance worldwide (McPherson and McPherson 2000; Schafer and Panizzi 2000). In general, they are polyphagous, feeding on a variety of cultivated and uncultivated plants and are active during most of the year. This is particularly true in areas of the world where the winter is mild and the average conditions are favorable to their development and reproduction, such as in the neotropics (Panizzi 1997). An important characteristic of most polyphagous stink bug pest species is their need for sequences of host plants in suitable phenological stages of development.

Studies on insect life history are fundamental to fully understand their bioecology and, therefore, to devise sustainable control measures against pest species within the concept of holistic integrated pest management (IPM) programs (Kogan and Jepson 2007). With regard to stink bugs, not many studies have focused on their life events throughout the different seasons. One possible reason for this is that

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research is often performed by economic entomologists and focuses on crop plants. They tend to not investigate stink bug populations on natural vegetation, including host and associated wild plants, and little attention is given to uncultivated land. In the past, this was considered acceptable because these insects were largely deemed less important. The priority in research was to concentrate on pests that cause damage to crop. However, to develop robust and sustainable stink bug management programs, research efforts should investigate their entire life history, which includes their characteristics when not present on crop plants.

Van Emden (1965a, b) was one of the first entomologists to recognize the role of uncultivated land in the distribution and abundance of pest insects and their natural enemies on adjacent crops. Regarding pest stink bugs, Miner (1966) carried out pioneering research on abundance of the green stink bug, *Chinavia* (*Acrosternum*) *hilare* (Say), and the southern green stink bug, *Nezara viridula* (L.) on soybean crops as well as in adjacent wooded plants. Populations on the crop were larger in areas cultivated near wooded areas, and the first generation was completed on wild hosts before invading crop fields. More recently, several studies have concentrated on exploring the roles of host plants (wild and cultivated), trap plants, overwintering habitats, and the management of farmscape ecology in order to devise ecologically sound management strategies and tactics for stink bugs and, in particular, enhance biological control by means of conservation (Jones and Sullivan 1981, 1982; Hokkanen 1991; Panizzi 1997; Ehler 2000; Mizell et al. 2008; Haseeb et al. 2016; Stahl et al. 2021).

In this article, we present different aspects related to the life history of stink bugs and how such studies can offer valuable information to support their biological control through conservation of their natural enemies. We will concentrate on pest species of major commodities, such as soybean, maize, and wheat in the Neotropical Region, where these insects are major pests and where several studies have been recently conducted. We covered in detail some species life history, the role of wild vegetation in their bioecology and natural enemies' conservancy, and how to promote balanced farmscapes considering crop and uncultivated areas.

Concept of life history studies and examples of pest stink bugs

The life history concept, applied to any species of insect, is a comprehensive approach to develop a detailed understanding throughout the entire year of the activity and characteristics of a particular species. This approach involves studying the various activities that a species engages in, such as exploration of food sources and reproduction, as well as tracking the progress of their offspring as they develop and produce future generations. The timing of these events is often influenced by a range of biotic and abiotic factors, the species' ability to adapt to favorable and unfavorable conditions, and landscape characteristics and spatial heterogeneity (Forman 1995). The present work is the first comparative summary of the life histories of these four stink bug species in this geographical area. We compiled the life history descriptions of these insects by conducting a literature review and by summarizing relevant findings from our own field experience.

In Table 1, we provide a comprehensive summary of the main components of the life history of pest stink bugs in the neotropics. These components include the number of generations completed on crops and on wild plants, the number of plants used as hosts where the insects can develop and reproduce, the number of associated plants used as food sources and/or shelter, and the number of species of egg and nymph/adult parasitoids found in the literature. The number of generations of stink bugs in the neotropics ranges from four to six, depending on the species. Furthermore, stink bugs use a varying number of plants, with the most polyphagous species *N. viridula* using as many as 77 different plant species. Parasitoids, which are important natural enemies of stink bugs, mostly target stink bug eggs, with the highest number of parasitoid species attacking *P. guildinii* eggs.

The behavior of pest stink bugs can vary significantly due to differences in environmental conditions, crop types, and landscape characteristics. To illustrate this concept, we showed schematic representations of pest stink bug populations on major commodities in the neotropics. We considered two different ranges of latitudes that cover the primary cultivation areas for these crops. The first range (range A) extends from 10° S to 23° S and covers the sub-tropical warm area

Table 1 Components of the life history of pest stink bugs in the neotropics on crops and wild hosts, considering number of generations completed, number of host and associated plant species used, and number of species of egg and nymph/adult parasitoids recorded

Species	Number of generations			Number of plants[c]			Number of parasitoid species		
	Crops[a]	Wild plants[b]	Total	Host	Associated	Total	Eggs	Nymphs/ adults	Total
Euschistus heros	4	2	6	7	25	32	10	5	15
Diceraeus melacanthus	4	2	6	6	25	31	9[d]	2	11
Nezara viridula	3	1	4	34	43	77	13	2	15
Piezodorus guildinii	3	1	4	25	28	53	17	2	19

[a] Mostly on soybean/maize crops

[b] Mostly on wild plants plus other minor crops

[c] Cultivated and non-cultivated plants acting as host or simply associated

[d] Egg parasitoid incidence on *Diceraeus* spp.; data based on Panizzi (1997), Smaniotto and Panizzi (2015), Zerbino and Panizzi (2019), and Panizzi and Lucini (2022)

(Fig. 1a). The second range (range B) covers the sub-temperate zone and extends from 23° S to 36° S, from the Tropic of Capricorn to the most southern latitude where the major commodity crops are grown (Fig. 1b).

Range A: 10° S to 23° S latitude (sub-tropical)

The relative abundance of stink bugs in the sub-tropical warm area is depicted in Fig. 1a. The population of stink bugs begins to increase in early spring (October) and reaches its peak in late spring/early summer (December), remaining high until mid-autumn (May), which is when the second crops are harvested. During the spring, they colonize the so-called first crops, which consist of soybean, maize, and cotton. As these crops are harvested, the insects move to nearby plants and disperse to the so-called second crops, which include the former crops plus beans and sorghum, cultivated in sequence. As the second crops are harvested during late autumn/early winter, the stink bugs move to host/associated plants and/or shelter niches until they start colonizing the following first crops in early spring again. Interestingly, in this area, stink bugs remain in relatively high numbers for about eight months and are mostly active on alternate plants, in smaller numbers, for the rest of the year. Although several species of stink bugs occur as pests on the major commodity crops of the sub-tropical warm area, two main species, the neotropical brown stink bug *Euschistus heros* (F.) and the green-belly stink bug *Diceraeus melacanthus* (Dallas), encompass about 80% of the populations.

Euschistus heros (F.)

The Neotropical brown stink bug is the most abundant species in the sub-tropical warm area of the neotropics. Its phenology has been previously presented and discussed in northern Paraná state, Brazil (latitude 23° 17′ S; Panizzi 1997). Over the course of 20 years, with the intensification of cropping systems and the addition of multiple crops in sequence in this warm area of the neotropics, further generations were added into Panizzi (1997)'s life history study. In Fig. 2a, we show the phenology of *E. heros*. At least four generations are completed on soybean, cultivated from early spring (October) as a first crop throughout early autumn (May), when the second soybean crop is harvested.

Two additional generations are completed as the stink bugs move to other cultivated plants (beans, cotton, sorghum) and to non-cultivated hosts/associated plants in late autumn and winter to complete their life cycle. Although *E. heros* spends part of its lifetime on the ground in partial hibernation (oligopause; Panizzi and Niva 1994; Panizzi 1997), with the expansion of cultivation in the sub-tropical warm area, this behavior became less common as food became available almost year-round. Furthermore, along with the cultivated crops, several weed plants grown in abundance provide additional food sources, such as *Bidens pilosa* L. (Asteraceae), *Euphorbia heterophylla* L.

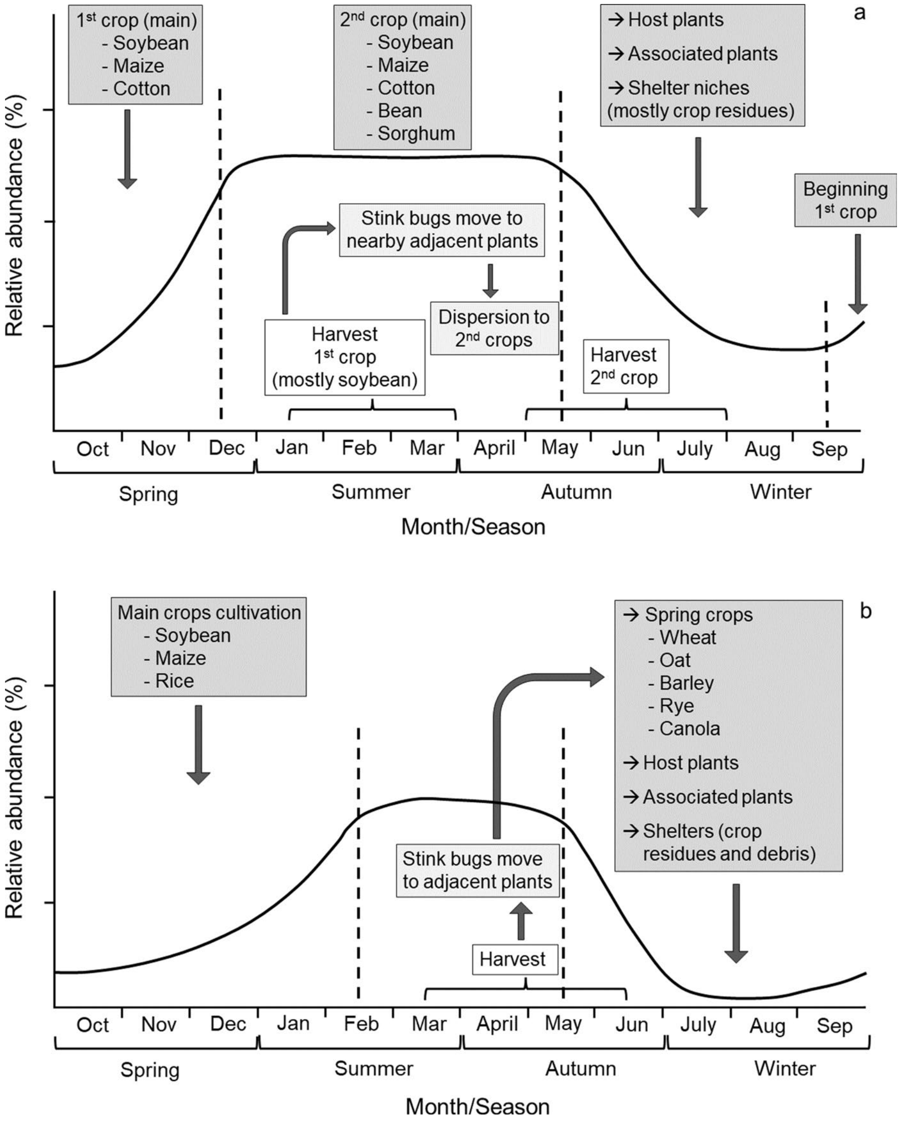

Fig. 1 Schematic representation of the behavior of pest stink bug populations on major commodity crops in the neotropics. **a** Populations in latitudes of the sub-tropical warm area (10° S to 23° S); and **b** populations in the sub-temperate area, from the Tropic of Capricorn (23° S) to the southern latitude of 36° S. Note that populations peak on crops, and, as they mature, they decrease and move to adjacent plants (hosts or not) or move to shelters on the soil below crops or other plant residues or debris

(Euphorbiaceae), *Brachiaria plantaginea* (Link) Hitch. (Poaceae), *Indigofera* spp. (Fabaceae) (see Panizzi and Lucini 2022 for more examples), helping to sustain populations of this and other species of stink bugs.

Diceraeus melacanthus Dallas

The green-belly stink bug is, in general, the second most abundant species in the sub-tropical warm area of the neotropics and possibly the most abundant in some locations (LM Vivan, personal communication). The phenology of this pest stink bug follows, in general, that of *E. heros* (Fig. 2b). It also completes six generations, which explains its present pest status in this area. *Diceraeus melacanthus* is a major pest of maize. Since it was first reported to damage maize seedlings in central–west Brazil in the 1990s (Ávila and Panizzi 1995), it became more relevant as a maize pest, requiring chemical control early in the season (Martins et al. 2009). This species is not able to develop and reproduce while feeding on seedlings (either of maize or wheat; Chocorosqui and Panizzi 2008), and seedlings mostly provide hydration as the insects feed on the xylem vessels (Lucini and Panizzi 2017).

Interestingly, *D. melacanthus* is the only pest stink bug that consistently feeds on cultivated maize

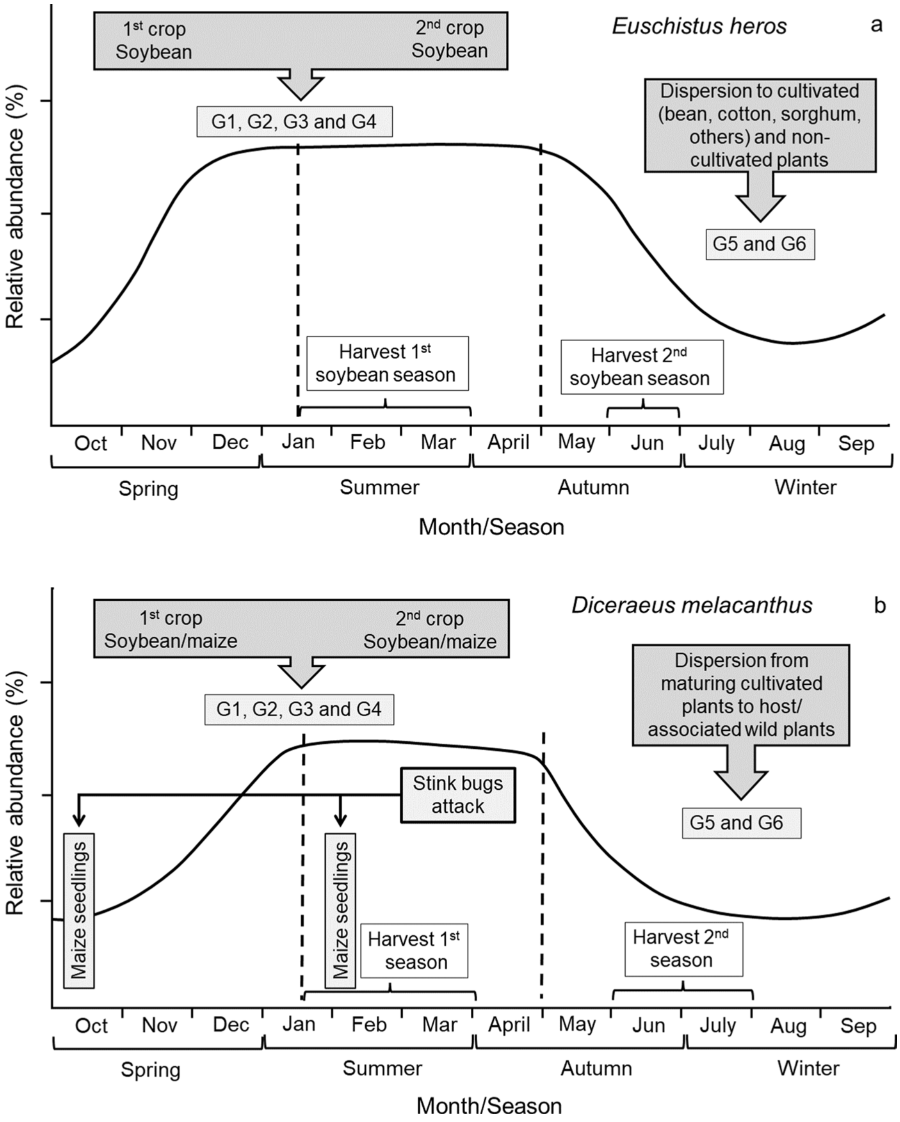

Fig. 2 Schematic representation of the dynamics of populations of several generations of **a** the Neotropical brown stink bug, *Euschistus heros,* and of **b** the green-belly stink bug, *Diceraeus melacanthus,* on major commodities in the neotropics in latitudes of the sub-tropical warm area (10° S to 23° S) (based on Panizzi 1997, Vivan LM, unpublished)

seedlings. Therefore, the combination of *D. melacanthus* feeding on reproductive structures of soybean plants and on maize seedlings in the first and second crops over about six months with its association with wild non-cultivated plants during the remainder of the year, helps sustain and grow populations.

Range B: 23° S to 36° S latitude (sub-temperate)

The abundance of stink bugs in the sub-temperate zone is shown in Fig. 1b. In this region, stink bug populations are relatively smaller than in the sub-tropical warm area. Further, the same crop is not cultivated in sequence in this area as in the warmer areas, which affects the abundance of the stink bug populations. At more southern latitudes, low temperatures are more frequently observed, restricting stink bug populations. Populations start to increase during spring (October), but in contrast to Range A, peak later (February/March).

As crops are harvested (March–May), stink bugs start to move to adjacent plants such as spring crops, which include several species of cultivated cereals (wheat, oat, barley, rye) and canola. As temperatures decrease in mid/late autumn (May/June), they also move to other associated/host wild plants and to shelters, which include crop residues and debris. In contrast to Range A, stink bugs in Range B are present in high numbers for about four months, decreasing thereafter and remaining mostly inactive over late autumn/winter in shelters.

Similar to what was observed in Range A, several species of pest stink bugs occur in the sub-temperate zone. Here, we focus on the main two species (although *E. heros* is observed in great numbers in this area in Brazil, it becomes rarer [in Argentina] or absent [such as in Uruguay]) as one moves south.

Piezodorus guildinii (Westwood)

The redbanded stink bug, *P. guildinii*, occurs in the sub-tropical warm area of the neotropics in low numbers and colonizes soybean in great numbers in the sub-temperate zone. Figure 3a shows that the first generation is completed during spring on other fabaceous crops, such as alfalfa (*Medicago sativa* [L.], red clover (*Trifolium pratense* [L.]), birdsfoot trifoil (*Lotus corniculatus* [L.]), wild indigo (*Indigofera* spp.), and wild *Crotalaria* species.

In late spring/early summer, *P. guildinii* moves to soybean crops, where it completes three additional generations. Soybean is harvested in late May, and this species then moves to other plants, usually trees such as sweet pittosporum (*Pittosporum undulatum* [Ventenat]; Pittosporaceae) and privet (*Ligustrum lucidum* [Aiton]; Oleaceae); in addition, it seeks

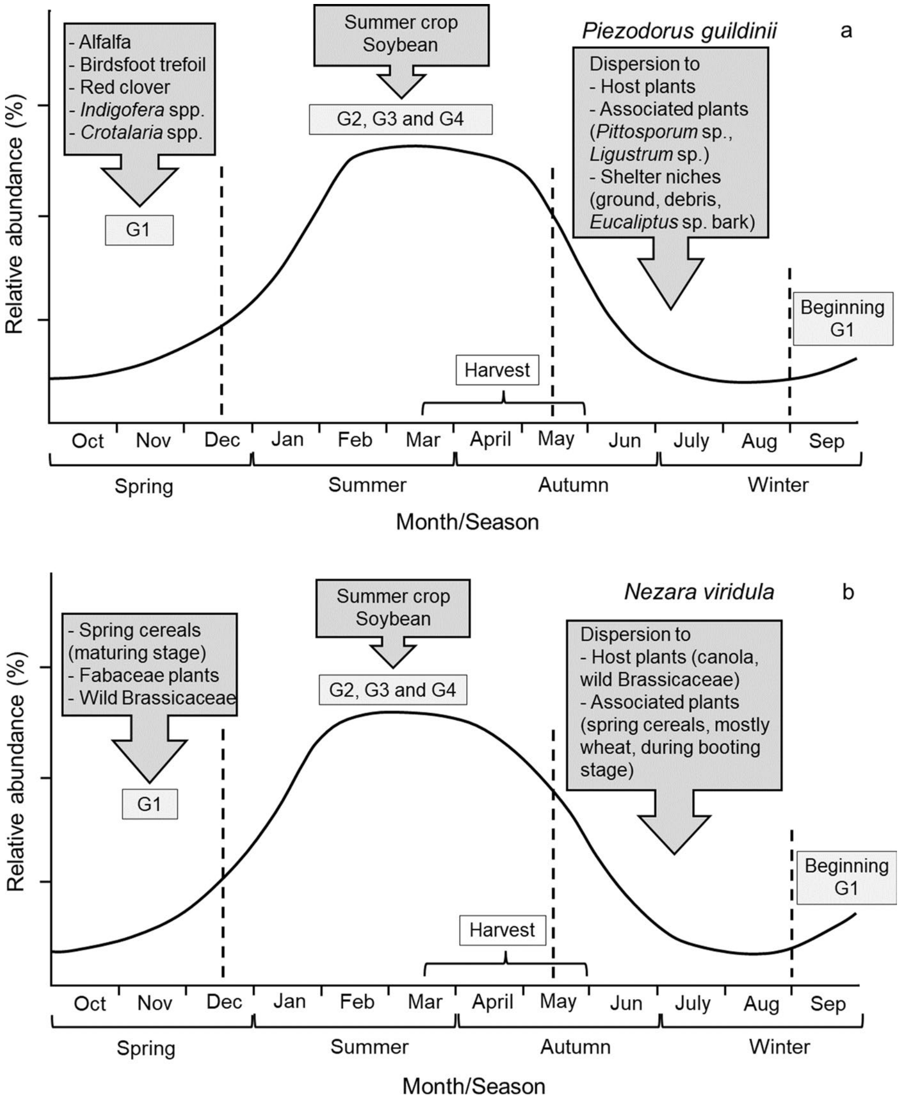

Fig. 3 Schematic representation of the behavior of populations of several generations of **a** the redbanded stink bug, *Piezodorus guildinii,* and of **b** the southern green stink bug, *Nezara viridula,* on major commodity crops in the neotropics in latitudes of the sub-temperate area from the Tropic of Capricorn (23° S) to the southern latitude of 36° S (based on Panizzi 1997; Zerbino et al. 2015, 2020)

protection in leaf litter of bamboo, *Phyllostachys* sp. (Poaceae), and *Eucalyptus* sp. (Myrtaceae), which provide some nutrients in addition to the primary role of shelter from the lower temperatures of late autumn and winter.

Nezara viridula (L.)

Similar to the previous species, the southern green stink bug completes its first generation on wheat and other spring cereals (oat, barley, rye), on wild and cultivated legumes, and on wild brassicas (*Raphanus* spp.; Brassicaceae) during early spring (October/November), before moving onto soybean crops (Fig. 3b). There, it completes three more generations until late May, during autumn, when the soybean crop is harvested. Thereafter, populations decrease and spread out looking for shelter during July/August, in winter. At the end of the winter, with the increase of temperatures, *N. viridula* then leaves the shelter and moves to the spring cereals in the booting stage, to canola in the reproductive stage, and to the wild brassicas to end its life cycle and to start again with the first generation.

Natural enemies and their use in reducing stink bug damage

Stink bugs are known to be susceptible to attacks by a wide range of natural enemies including parasitoids, predators, and entomopathogens. Despite this, the potential role of these natural enemies in controlling stink bug pests has been underestimated, particularly in southern South America (Zerbino and Panizzi 2019). This area is part of the Neotropical Region, the most diverse and complex zoogeographic region in the world, indicating a significant potential for exploring and enhancing the impacts of natural enemies on stink bug populations.

Parasitoids

Several parasitoids have been found to be effective against stink bugs, including egg and nymph/adult parasitoids. Egg parasitoids are parasitic wasps that lay their eggs in or on the eggs of other insects. These parasitoids are an important part of natural pest control and can be used to help mitigate the abundance of pest stink bugs. Egg parasitoids can be effective in reducing populations because they attack stink bug eggs before they hatch, preventing progenies emergence. At least 23 species of egg parasitoids are known to attack the eggs of the stink bugs that are soybean pests, with the main ones in the Neotropical Region being *Telenomus podisi* (Ashmead), and *Trissolcus basalis* (Wollaston) (Hymenoptera: Scelionidae) (Bueno et al. 2012).

To enhance the service of egg parasitoids, it is important to provide suitable habitats for these insects. This can be done by planting specific plants that are known to attract egg/nymph/adult parasitoids, for example wildflowers, such as *Asclepias tuberosa* L. (Asclepiadaceae), and the Asteraceae plants *Leucanthemum vulgare* Lam., *Achillea millefolium* L., *Solidago rugosa* Mill., *Solidago speciosa* Nutt. and *Eupatorium perfoliatum* L. (see Hatt et al. 2018; Dively et al. 2020 for further details). Additionally, reducing the use of broad-spectrum insecticides can help to preserve the natural enemies that help to control stink bug populations.

Nymphs and adult parasitoids of stink bugs include parasitic flies and wasps that lay their eggs in or on the bodies of other insects. The most common species of parasitoids attacking nymphs and adults of stink bugs in the Neotropical Region are the fly *Trichopoda giacomelli* (Blanchard) (Diptera: Tachinidae) and the wasp *Hexacladia smithii* (Ashmead) (Hymenoptera: Encyrtidae) (Bueno et al. 2012).

Parasitoids of eggs and adults stink bugs can be attracted to certain plants, such as those that produce nectar and pollen. By planting or maintaining these plants near stink bug-infested areas, habitats can be created that are conducive to the survival of nymph and adult parasitoids, which can help to increase their numbers and effectiveness in controlling stink bug populations.

Predators and entomopathogens

A largely and understudied group of insects is those that carnivorously feed on nymph and adult pest stink bugs. Although most predators prefer to feed on soft-body caterpillars, some do prey on young stink bug nymphs and even adults. These include some hemipterans (e.g., *Podisus* spp., *Tynacantha* spp., *Geocoris* spp., *Nabis* spp., *Orius* spp.), coleopterans (e.g., *Callida* spp., *Lebia* spp., *Calosoma* spp., *Eriopsis* spp.)

and species of ants, wasps, and related arthropods (mites and spiders) (Bueno et al. 2012).

Among the entomopathogens (bacteria, fungi, viruses) that have been shown to be effective against stink bugs are the fungi *Beauveria bassiana* Vuillemin, *Metarhizium anisopliae* Sorokin, and *Cordyceps* spp. To enhance the service of these natural enemies, it is important to avoid the use of fungicides and other chemicals that can kill them and to promote healthy soil and plant communities through practices such as crop rotation and cover cropping.

Wild (uncultivated) vegetation and bioecology of stink bugs and their natural enemies

The impact of wild vegetation has received considerable attention, where such vegetation provides shelter or alternate hosts for stink bug pests when preferred hosts plants are not available (Panizzi 1997; Panizzi and Lucini 2022). It can help populations to increase, and if they then move into cultivated crops, increased damage can result. On the other hand, there is the possibility of non-hosts intercepting the pests before they reach the crop, resulting in less damage. Then there is the possibility of non-crop plants being consistently more attractive than the main crop, which can reduce damage. This is the main goal of trap-cropping. Most of the trap crops have been cultivated plants, because of the need to manage and to keep them in conditions that make them more attractive than the crop plants. In contrast, the role of native vegetation in supporting populations of natural enemies of stink bugs has received little attention. However, there has been some investigation of effect of purposefully planting native plant species on populations of natural enemies of insect complexes that include stink bugs (e.g., Morandin et al. 2014).

Stink bugs feed on a wide range of plant species, including cultivated and non-cultivated (wild) plants. These can be classified as host or associated plants. Wild vegetation can have significant effects on the bioecology of stink bugs and their natural enemies. When wild vegetation is present in and around crops, natural enemies are, in general, more abundant and diverse (Altieri 1994; Bianchi et al. 2006), which help to keep stink bug populations in check through predation or parasitizing eggs/adults.

Wild vegetation can also affect stink bug bioecology by altering their behavior. Phytophagous insects use multiple olfactory and/or visual plant cues to guide them to resources used for food and reproduction (Bernays and Chapman 1994), and the presence of wild vegetation can interfere with their ability to do so. This can lead to reduced damage and reproductive success as well as increased vulnerability to natural enemies (e.g., Pease and Zalom 2010; Letourneau et al. 2011; Morandin et al. 2014).

Role of host and associated plants

Plants can be characterized based on their role in relation to stink bugs. On one hand, there are host plants, which are those that allow nymph development and/or adult reproduction. These play the most important role in stink bug bioecology because this is where progeny is produced, and several generations follow in sequence, resulting in population increases. On the other hand, there are associated plants, which provide nutrients, water, and/or shelter but do not allow nymph development and adult reproduction. The role of these plants is secondary but also important in the bioecology of stink bugs, as they fill gaps in their life cycle (Smaniotto and Panizzi 2015; Panizzi and Lucini 2017).

Role of annual weed plants

With the recent intensification of cropping systems and the wide adoption of no-tillage cultivation in the neotropics, annual weed plants have drastically increased in abundance (Panizzi et al. 2022). Because many of them serve as hosts of several species of pest stink bugs, the insects rely on them to complete development and to reproduce. The ones that serve as associated plants sustain populations by offering nutrients, water, and shelter (Panizzi and Lucini 2022). These plants support stink bugs but can also serve as hosts for natural stink bug enemies. Egg masses of several species of stink bugs collected from weed plants growing at crop margins are commonly parasitized by egg parasitoids (Loch and Walter 1999) and consumed by generalist predators (ants; Jones et al. 2001). For instance, eggs of *N. viridula* that were collected from multiple weed species exhibited a high degree of parasitism, ranging from 33 to 100%. Those collected on soybean plants showed a parasitism rate of 35% (Loch and Walter 1999).

The percentage of parasitism by tachinid flies on *N. viridula* adults is substantially greater when they concentrate on weeds on late autumn/spring (65–100%) compared to when they are primarily on soybean during summer/mid-autumn (30–55%; Panizzi and Oliveira 1999). Similarly, tachinid flies were shown to parasitize adults of another stink bug species, *Diceraeus furcatus* (F.) on the weeds *Brassica rapa* L. (Brassicaceae), *Brachiaria plantaginea* (Link) Hitch. (Poaceae), and *Digitaria sanguinalis* (L.) Scop. (Poaceae) (Agostinetto et al. 2018).

The Neotropical red-shouldered stink bug *Thyanta perditor* (F.), a pest of cultivated cereals, is heavily parasitized by at least seven species of tachinids when living on the weed *Bidens pilosa* L. (Asteraceae) (Lucini et al. 2020). The hymenopteran *H. smithii* was found parasitizing tomato stink bugs (*Arvelius albopunctatus* [De Geer]) that were collected from the weeds *Solanum palinacanthum* Dunal and *Solanum paniculatum* L. (Solanaceae) located in pasture lands at Londrina, northern Paraná state, southern Brazil (23° 18′ S; 51° 09′ W) (Panizzi and Silva 2010). Natural enemies often follow their prey onto wild vegetation, in this case annual weeds, as well as is to perennial wild hosts.

Role of perennial wild plants

Perennial wild plants (e.g., trees) are, in general, part of the agricultural landscape. However, in some flat, extensive areas, such as those of the central–west plains of the neotropics in Brazil (sub-tropical warm areas), thousands of hectares are cultivated with crops where there are no trees. In these areas, IPM programs are difficult to implement because of large crop field sizes, the standard use of aerial pesticide application, and a higher difficulty of monitoring (sampling) the incidences of pests compared with smaller field crops (Bueno et al. 2021). In addition, there is the general growers' concept that wild plants should not occupy areas that should be devoted to crops.

In the sub-temperate zone, the presence of perennial trees adjacent to crop fields is common, although wild vegetation in this area has also been partly decimated as a long-term consequence of cultivating the land. In contrast to the former large areas of the subtropics, IPM programs are more easily implemented here and used by growers. Although we could not find studies comparing the contrasting crop field situations between the sub-temperate and sub-tropical warmer areas, regarding pest incidence and the use of conservation biological control, it is generally believed that the former is a more balanced agroecosystem (Altieri and Letourneau 1982).

There are several examples of trees that may host some species of pest pentatomids and their natural enemies. Privet, *L. lucidum*, was found to host at least 13 species of pentatomids in Paraná, Brazil. In fact, its berries are used to feed colonies of stink bugs in laboratories (Panizzi and Grazia 2001). Other common trees that host stink bugs in the neotropics include sweet pittosporum (*P. undulatum*; Zerbino et al. 2015, Marsaro et al. 2020b) and the leguminous orchid tree *Bauhinia forficata* Link (Fabaceae), which is known to host several species of pentatomids (ARP, unpublished). Surveys performed on native trees in Rio Grande do Sul, Brazil, found *P. guildinii* on *Eugenia uniflora* L. and *Myrciaria tenella* (DC.) Berg (Myrtaceae); and *E. heros* on *Casearia sylvestris* SW. (Salicaceae) (Costa et al. 1995).

Parasitoids also follow the stink bugs onto perennial trees. Examples include tachinid flies that parasitize adults of the green-belly stink bug on a native perennial plant, the Brazilian pepper tree *Schinus terebinthifolius* Raddi (Anacardiaceae) (Agostinetto et al. 2018). Another natural enemy found on a perennial tree, *P. undulatum*, that hosts stink bugs is *Hexacladia hilaris* Burks (Hymenoptera: Encyrtidae) in Brazil, in association with *Chinavia erythrocnemis* (Berg) (Marsaro et al. 2020a).

The "ideal" landscape: balancing major cultivated and minor uncultivated areas

The use of monocultures over large areas present hazards to the natural enemies involved in biological control of insect pests, caused by the lack of structural diversity on monocultures. The limited availability of diverse food sources and habitats in monocultures reduces the resources for natural enemies, reducing their numbers and richness, which hind their ability to regulate insect pest populations (Altieri 1994). In consequence, pest outbreaks occur, and pesticides are overused, disrupting the ecosystem's balance.

The interaction between wild vegetation and the bioecology of stink bugs and their natural enemies is a multifaceted and dynamic relationship that is affected by a range of contextual factors (Panizzi et al. 2022). This relationship is particularly important in agricultural ecosystems, where the presence of wild vegetation, including annual weed plants in and around cultivated areas as well as perennial wild vegetation such as trees on the periphery of fields, is essential for attracting and maintaining a diverse array of natural enemies. Therefore, a comprehensive and holistic approach that takes into account the ecology of both stink bugs and their natural enemies, as well as the surrounding vegetation, is necessary for effective stink bug population management in agricultural and natural ecosystems. Such an approach should include careful consideration of the type and placement of wild (uncultivated) vegetation as well as the timing and frequency of management interventions to ensure the health and diversity of natural enemy populations and the effective control of stink bug populations.

In Fig. 4, we present relationship between natural vegetation, stink bugs, and their natural enemies, providing a theoretical representation of an "ideal" landscape that balances the needs of agriculture and wild vegetation. In this theoretical landscape, the primary area under cultivation is complemented by a secondary area dedicated to wild, uncultivated vegetation. These uncultivated areas serve as a refuge for natural enemies and enhance the service they provide within the context of conservation biological control. By creating this landscape, stink bug populations can be managed sustainably and naturally, reducing reliance on pesticides and promoting a healthy ecosystem.

Ideally, the cultivated area should be covered with multiple crops, which sometimes is not possible. In this case, the same crop should not be cultivated in sequence, and crops should be alternated. This avoids several problems, including an increase in pest incidence. Moreover, the use of several different crops provides different niches for natural enemies, increasing their effects on the pests (Altieri and Letourneau 1982; Altieri 2002).

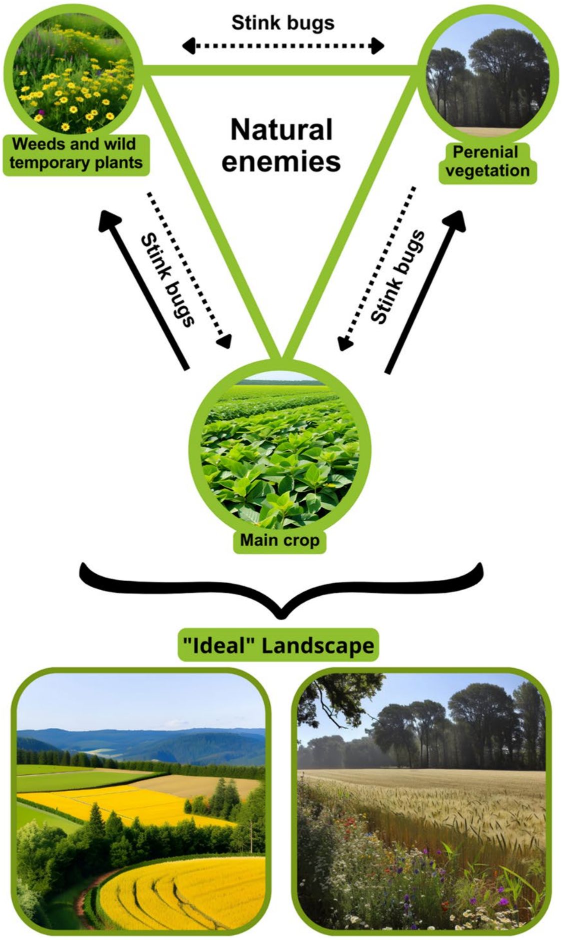

Fig. 4 Schematic representation of the relationship between natural enemies, stink bugs, and plants in an "ideal" agricultural system. The solid lines represent the primary flow of stink bugs from main crops to natural vegetation (wild perennial trees, annual weeds, and other temporary wild vegetation), the dashed lines indicate the secondary flow of stink bugs from or within natural vegetation to main crops. The "ideal" landscape in an agricultural system should encompass, in addition to an area covered with cultivated plants (the majority), a minor area devoted to non-cultivated plants (weeds and trees)

Within a field crop, the presence of adjacent areas of non-cultivated vegetation such as trees and wild plants can have a significant effect on the abundance and diversity of stink bugs and their natural enemies. Therefore, understanding how wild vegetation influences the colonization rates and population gradients of natural enemies in crop fields is critical. Research has shown that the density and diversity of natural enemies are higher in crop fields surrounded by certain types of vegetation compared with around vegetation-free fields, highlighting the importance of wild vegetation in supporting sustainable agricultural practices (Altieri and Letourneau 1982). By adopting a more integrated and holistic approach to managing stink bug populations, we can ensure the long-term health and sustainability of both agricultural and natural ecosystems.

Concluding remarks

Regarding the biological control of pest stink bugs, the abundant information available must be directed toward conservation biological control to achieve sustainable pest control. In a forum article, Michaud (2018) emphasized that, although biological control through augmentation has the benefit of replacing pesticides, it cannot be considered ecologically sustainable because inputs are often required, although sometimes it is required to guarantee an establishment of the natural enemies in the system. This type of biocontrol contrasts with the conservation biological control, which has more persistent beneficial effects and requires the management of agricultural habitats. Unfortunately, this type of biocontrol is not well-implemented in the neotropics compared with other regions of the world (Peñalver-Cruz et al. 2019; Vargas et al. 2023).

At least four main variables are involved in determining whether a given system will result in increased or decreased damage, and these variables need to be quantified for each system: (1) Ability of alternative hosts to support growth and reproduction of stink bugs, (2) ability of natural enemies to increase on alternative hosts, (3) effectiveness of natural enemies in reducing populations of stink bugs, and (4) size and timing of dispersion of both stink bugs and natural enemies to and from main crop and alternative hosts.

In conclusion, the analysis of stink bug pest life histories highlights the importance of conducting studies on associated natural enemies to develop sustainable IPM programs. Information on the pests and their control agents, most of the time scattered across sources, must be put together to allow better understanding of the agroecosystem.

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Declarations

Conflict of interest The authors claim no conflict of interest.

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Research involving human and animal rights The research involves no human participants and/or animals.

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