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RANGE EXPANSION AND INCREASING DAMAGE POTENTIAL OF PHYTOPHAGOUS SHIELD BUGS (Heteroptera: Pentatomidae)

(review)

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Abstract

During a few recent decades, in many regions of the world, there have been recorded expansion of ranges and an increase in the harmfulness of many stink bug species (Heteroptera: Pentatomidae) (A.R. Panizzi, 2015; J.E. McPherson, 2018). A leading role in these processes is probably played by the current climate change and unintentional introduction of phytophagous pentatomids as a result of intensified transportation of goods and development of tourism, coupling with natural polyphagy and high migratory potential of many pentatomids (D.L. Musolin, A.Kh. Saulich, 2012, A.M. Wallner et al., 2014; T. Haye et al., 2015; T.C. Leskey, A.L. Nielsen, 2018). In the south of Russia, since early XXI century there have been numerous records of increased population density and substantial damage caused to soybean, vegetable, fruit, and berry crops caused by the southern green stink bug *Nezara viridula* (L.) that previously had only limited distribution and damage in the region (M.V. Pushnya et al., 2017; A.S. Zamotailov et al., 2018). In Krasnodar Krai and Republics of Adygea and Crimea, losses of tomatoes, beans, cabbage, grapes, raspberries and other crops caused by this pest reached 70–90 % in some places in 2017–2019. On the Black Sea coast of the Caucasus (in Russia, Abkhazia, and Georgia), agricultural and ornamental crops are currently also seriously damaged by the invasive brown marmorated stink bug *Halyomorpha halys* (Stel) that was introduced to the region less than 10 years ago (I.M. Mityushev, 2016; D.L. Musolin et al., 2018). In different parts of its invasive range, this polyphagous pentatomid demonstrates tendencies to expand its' host plant range (D. Lupi et al., 2017; M.-A. Aghaee et al., 2018; S. Francati et al., 2021; V. Zakharchenko et al., 2020). At the same time, various wild plant species growing along forest edges and forest belts have recently become the major reserves of *N. viridula* and *H. halys* in the Caucasus and this greatly complicates the control of these pests (B.A. Borisov et al., 2020). Studies of seasonal development of the native Italian striped bug *Graphosoma lineatum* (L.) in the forest-steppe zone of the Belgorod Province demonstrated that currently this species often produces two annual generations, whereas in the 1990s the species had two generations during the growing season only in the exceptionally warm years with temperatures above the mean level (D.L. Musolin, A.Kh. Saulich, 2001). Currently, in European countries and Russia, a number of pentatomids, e.g., *Palomena prasina* (L.), *Dolycoris baccarum* (L.), *Eurydema ornata* (L.), *Pentatoma rufipes* (L.), and *Rhaphigaster nebulosa* (Poda), have increased population densities what is accompanied by increased damage caused by these species to cultivated crops and wild plants. In Central America, *Antiteuchus innocens* Engleman et Rolston was not previously considered a serious pest, but in recent years an increased abundance of this pentatomid has been recorded in Mexico,

what lead to a weakening of pine forests (F. Holguин-Melйndez et al., 2019). High population densities and increased damage to crop production caused by stink bugs are also facilitated by the absence or slow development of control measures against these invasive pests.

Key words: Hemiptera, Heteroptera, Pentatomidae, phytophagous insects, pests, harmfulness, population density dynamics, invasive species, climate change, *Nezara viridula*, *Halyomorpha halys*

Stink bugs (Heteroptera: Pentatomidae) are the largest family of hemipterans, including 10 subfamilies, 940 genera and approx. 4 950 species of phytophages, less often predators or zoophytophages [1-6]. The majority of pentatomid species are characterized by an annual life cycle synchronized with seasonal cycles of development of host plants, and overwintering at the adult stage [7]. In the Russian entomological literature of the XX century, pentatomids appeared mainly as secondary pests of almost all groups of agricultural crops [8-9]: cereals [10], technical [11], vegetables and potatoes [12], annual and perennial grasses [13], fruit and berry crops [14], sugar beet [15].

According to the most complete reference book among agricultural pests [16], only 10-15 species of the pentatomids were periodically economically significant. These are several species in the genus *Eurydema* (*E. oleracea* (L.), *E. ventralis* Kolenati, *E. ornata* (L.), *E. maracandica* Osh. et al.), trophically related to the species of the family *Brassicaceae*; bugs of the genus *Aelia* (*A. acuminata* (L.), *A. klugii* Hahn, *A. rostrata* Bohemian, *A. sibirica* Reuter) on cereals; *Graphosoma lineatum* (L.), harmful to plants of the family *Apiaceae*; polyphages *Carpocoris purpureipennis* (De Geer) and *Dolycoris baccarum* (L.). Nevertheless, according to the economic damage extent, all of them were much inferior to bugs from a closely related family of shield bugs (Scutelleridae) – *Eurygaster integriceps* Puton, *E. austriaca* (Schrank) and *E. maura* (L.) [17].

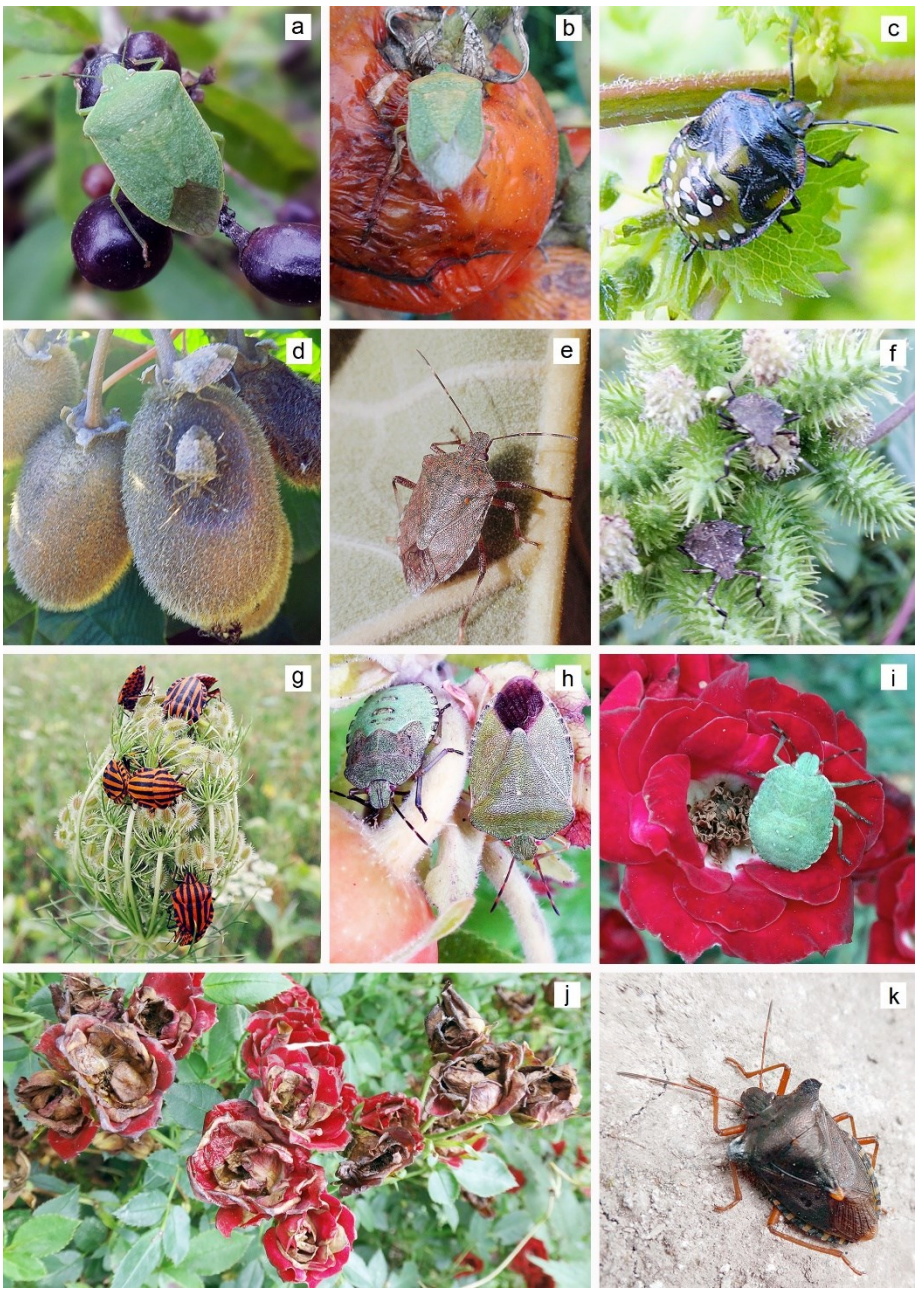
Foreign researchers also pointed to the relatively low harmfulness of pentatomids in the past [18, 19]. The most dangerous species in various regions previously included *Murgantia histrionica* (Hahn) (feeding on cruciferous crops) [20]; *Mormidea quinqueluteum* (Lichtenstein) and *Arvelius albopunctatus* (De Geer) (on nightshades and rice, respectively) [21, 22]; *Aelia furcula* Fieb. (on wheat *Triticum* L. and barley *Hordeum vulgare* L.) [23]; *Agonoscelis pubescens* (Thunberg) [on sorghum *Sorghum* Moench and sesame *Sesamum indicum* L.) [24].

However, since the end of the XX century, many insect species, including pentatomids, have had a noticeable expansion of their ranges [18, 25-28], an increase in population density [29-31], and/or in harmfulness [30-32] in different parts of their ranges. This is probably due to global climate change (which usually manifests itself in milder winter conditions, lengthening of the growing season, etc.) [26, 27, 33-36], intensification of global transport flows and increase in mass tourism [35, 37].

The purpose of this review is to comprehensively identify and analyze the causes and scale of numerous, but disparate examples of changes in the ranges and the level of harmfulness of pentatomids in Russia and other countries in early XXI century.

The southern green stink bug *Nezara viridula* L. (Fig., a-c), originating from northern Africa [38], in the later XX century, has begun to spread around the world as one of the first among pentatomids, causing economic damage to various agricultural crops, especially soybeans (*Glycine max* (L.) Merr.) [39]. During the recent decades, the situation with this phytophagous pest has worsened in many European countries: Great Britain [40], Romania [41], Germany [42], Slovakia [43], Poland [44], the Czech Republic [45], as well as in Turkey [46], Cuba [47], in Argentina [48], Brazil [49], India [50], Japan [51, 52], Australia [53], etc.

The harmfulness of this species is greatly impaired by its ability to transmit phytopathogenic microorganisms [54-56]. As it was shown, the shift of the northern border of its range is directly related to the increase in winter temperatures [57].



Pentatomids on the plants they damage. The southern green stink bug *Nezara viridula*: a — an adult on fruits of common privet (*Ligustrum vulgare*) (Republic of Adygea, 2019), b — an adult on a fruit of tomato (*Solanum lycopersicum*) (Republic of Adygea, 2018), c — a nymph on a leaf of shrub perilla (*Perilla frutescens* (L.) Britton) (Sochi, 2021); brown marmorated stink bug *Halyomorpha halys* (Sochi, 2018): d — an adult on fruits of kiwi (*Actinidia deliciosa*), e — an adult on a catalpa leaf (*Catalpa bignonioides*), f — nymphs on common cocklebur (*Xanthium strumarium*); g — Italian striped bug *Graphosoma lineatum* in inflorescences of wild carrot (*Daucus carota*) (Belgorod Province, 2021); the green shield bug *Palomena prasina* (Moscow Province, 2018): h — an adult and a nymph on rosehip (*Rosa* sp.), i — a nymph on the rose flower (*Rosa* sp.), j — rose flowers damaged by *P. prasina*; k — red-legged shield bug *Pentatoma rufipes* (Belgorod Province, 2020).

In the former USSR, the southern green stink bug was known as a not-

numerous inhabitant of natural ecosystems in the south of the Crimea and Transcaucasia which only occasionally caused damage to bean crops in Georgia [16]. However, since 2006 it has been recorded in the steppe regions of Krasnodar Krai as a significant pest on soybeans [58, 59]. In recent years, cases of mass colonization of *N. viridula* on vegetable crops, such as tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.), eggplant (*Solanum melongena* L.) have become more frequent, and damage to plants by the southern green stink bug is very significant [59, 60]. In Krasnodar Krai, this pest causes serious losses to farmers who have to complete the cultivation of tomatoes a month and a half earlier than they usually did [32]. In Stavropol Krai, since 2017, outbreaks of *N. viridula* have also taken place in greenhouses, where the pest damaged cucumber greens (*Cucumis sativus* L.) to a non-marketable state [N.I. Budynkov, Russian Research Institute of Phytopathology, personal communication). An increase in the harmfulness of the species has also been noted on tobacco plants (*Nicotiana tabacum* L.) [61].

Currently, the adaptation of *N. viridula* to new conditions in the south of Russia continues, there is an expansion to new host plants. The species is characterized by high fecundity, ability to form aggregations and multivoltinism (in favorable years it can produce up to three generations per season). To a greater extent, harmfulness manifests itself in dry hot weather [57, 59].

In the summer months of 2017-2019, the number of nymphs and adults of *N. viridula* in some farmlands of Adygea reached 40-50 specimen/m^2, which caused significant crop losses of tomatoes (up to 30-70%), sweet pepper and squash (*Cucurbita pepo* L. subsp. *ovifera* (L.) D.S. Decker), bean (*Phaseolus vulgaris* L.), cabbage (*Brassica oleraceae* L.), grape (*Vitis vinifera* L.), raspberry (*Rubus idaeus* L.) and other crops (62). In 2019, this was observed in the Crimea, where the shortage of tomatoes in household plots reached 70-90% (E.N. Zhuravleva, unpublished data).

The main reservoir of this phytophagous pest in the southern regions of Russia turned out to be not agricultural crops, but various plants of natural and ruderal flora on the outskirts of forests and along old forest belts, where the largest concentrations were observed on elderberry (*Sambucus nigra* L.) and wild privet (*Ligustrum vulgare* L.) [62]. In the humid subtropical zone, the population density of *N. viridula* is still substantially lower, but the patterns are the same [62].

In 2014, following the USA and European countries, a very dangerous alien pest of the East Asian origin – the brown marmorated stink bug *Halyomorpha halys* (Stel) (see Fig., d-f) [63, 64] arrived at Russia, on the Black Sea coast of the Caucasus. At the same time, the potential of the species for further settlement is assessed as very high not only by foreign researchers [65], but also by Russian scientists: it is assumed that the phytophagous pest can adapt on the territory of the European part of Russia, up to Kursk, Belgorod, Voronezh and Saratov regions [66].

Since 2016, this phytophagous pest has caused impressive crop losses of citrus fruits in the humid subtropics of Russia: primarily tangerine (*Citrus reticulata* subsp. *unshiu* (Marcow.) D. Rivera & al.), apple (*Malus domestica* Borkh.), pear (*Pyrus communis* L.), peach (*Prunus persica* (L.) Batsch), persimmon (*Diospyros kaki* Thunb.), fig (*Ficus carica* L.), hazelnut (*Corylus avellana* var. *pontica* (K. Koch) H.J.P. Winkl.), bean, tomato, sweet pepper, corn (*Zea mays* L.) and others [64]. During 6 or 7 years of its presence in the humid subtropics of Russia, the range of host plants damaged by this pentatomid has exceeded 100 species from many families. Among tree and shrub species, it is often found on cherry laurel (*Prunus laurocerasus* L.), southern catalpa (*Catalpa bignonioides* Walter),

princess tree (*Paulownia tomentosa* Steud.), common mulberry (*Morus alba* L. and *Morus nigra* L.), common hazel (*Corylus avellana* L.), beech (*Fagus orientalis* Lipsky), lime tree (*Tilia begoniifolia* Steven), ash tree (*Fraxinus excelsior* L.), blackberry (*Rubus caucasicus* Focke and other species), and among herbaceous plants — on common cocklebur (*Xanthium strumarium* L.), thistle (*Cirsium* spp.), cockspur (*Echinochloa crus-galli* (L.) P. Beauv.), bittersweet (*Solanum dulcamara* L.) [67].

In other parts of the invasive range of *H. halys*, there is also an expansion of trophic connections of this species. Thus, for the first time it was noted as a pest of rice (*Oryza sativa* L.) in northern Italy in 2017 [68], and since 2018 — in California [69]. Significant damage by this species to kiwi (*Actinidia deliciosa* (A. Chev.) C.F. Liang & A.R. Ferguson) was recorded in Italy in 2018-2019 [70]. Since 2019, that is 4 or 5 years after its appearance in Romania, *H. halys* begun to show increased harmfulness to garden and ornamental plants [71].

Serious concerns are caused by the ability of *H. halys* (as well as a number of other pentatomids) to carry the yeast fungus *Eremothecium coryli* (Peglion) Kurtzman (Ascomycota, Saccharomycetales), which can cause mass rot of tomato fruits [72] and lead to economically significant loss of hazelnut kernels [73].

In the Eastern Black Sea region, the main reservoirs of *H. halys* are natural plantings, where its number is immeasurably higher than in the agricultural sector and on ornamental plantings. Massive aggregations of the pest have been noted in protected natural areas (in the forests of Sochi National Park and the Caucasian State Natural Biosphere Reserve), where, according to modern legislation, the use of pesticides is unacceptable [62]. Thus, it is not possible to eradicate *H. halys*, although it is required according to the Federal Service for Veterinary and Phytosanitary Surveillance regulations regarding quarantine pests. Due to the high migration ability of this pest at the adult stage and its wide polyphagy, even a protection system coordinated between different departments is doomed to low efficiency. The only measure to control *H. halys*, which, with a well-coordinated organization, might give a positive result, is the manual collection of adults in places of their mass overwintering (attics of houses, sheds, timber warehouses, stacks of firewood, etc.) with subsequent immediate destruction [62]. However, such practice cannot solve the problem cardinally.

The extension of the growing season is one of the important consequences of the climate change, especially in temperate latitudes [26, 74]. This, in turn, may contribute to an increase in the number of generations realized by phytophagous insects during a year [36]. Thus, in the 1990s, it was shown that under the conditions of the forest-steppe of Belgorod Province, the Italian striped bug *Graphosoma lineatum* (L.) (see Fig., g) is usually univoltine but can give two generations per season only in the warmest years [75]. Two decades later, in 2019-2021, according to the observations in Shebekinsky District of this region, the bivoltinism of the species probably became normal. Mass emergence of adults was observed not in mid-July (as it was in the past), but almost a month earlier (in late June), and in late September there was a very high number of adults (especially on the ubiquitous wild carrot *Daucus carota* L.), which at the end of the growing season could hardly be like that with the development of only one generation per season (B.A. Borisov, unpublished data).

A frequent consequence of the steady increase in average temperatures is the better survival of many insects during overwintering, and in summer — an increase in fecundity, which strongly depends on the available amount of effective temperatures among poikilothermic organisms [34]. Probably, this can explain the increase in population density of some pentatomid species observed in different regions of Russia in recent years. According to the long-term observations in

different districts of Moscow Province, the abundance of the previously relatively not-numerous, albeit common, native green shield bug *Palomena prasina* (L.) (see Fig., h-j) has increased many times in 2016-2020 both in household gardens (on bean *Phaseolus* L., broad bean *Vicia faba* L., black chokeberry *Aronia melanocarpa* (Michx.) Elliott, rose *Rosa* spp., tatarian dogwood *Cornus alba* L.), and on the edges of woodlands (on stinging nettle *Urtica dioica* L., dead-nettle *Lamium* spp., hemp-nettle *Galeopsis tetrahit* L., three-lobe beggarticks *Bidens tripartita* L., touch-me-not *Impatiens noli-tangere* L., burdock *Arctium lappa* L., raspberry, blackberry, rosehip *Rosa* spp., snowy mespilus *Amelanchier ovalis* Medik., rowan *Sorbus aucuparia* L., alder buckthorn *Frangula alnus* Mill., guelder-rose *Viburnum opulus* L.). Numerous symptoms of plant diseases have been noted in the places where this species is gathered: on raspberry — a strong development of viral infections transmitted by this bug (crinkle and chlorosis of leaves), on snowy mespilus — damage of berries by monilia, on roses — browning and drying of flowers impaled by the pest due to the development of bacteriosis (see Fig., j) [62].

In recent years, similar situations have been noted in Moscow Province with the native sloe bug *Dolycoris baccarum* (L.) (B.A. Borisov, unpublished data). In July 2020, in a number of farm fields throughout Belgorod Province, abundance of this species and of black-shouldered stink bug *Carpocoris purpureipennis* (De Geer) on ears of bread wheat (*Triticum aestivum* L.) was noticeably higher than of the "traditional" pest − the sunn pest *Eurygaster integriceps*. It is opposite to what had been usually observed (B.A. Borisov, unpublished data).

Also, in recent years, not only an increase in the harmfulness of *P. prasina*, *D. baccarum*, *Eurydema ornata*, *Aelia acuminata*, *Rhaphigaster nebulosa* (Poda) and *Graphosoma semipunctatum* (F.) (a species typical to the Mediterranean region) was noted, but also a high density and prevalence of these species in Azerbaijan [76].

The usual trans-Palearctic red-legged shield bug *Pentatoma rufipes* (L.) (see Fig., k), associated with trees and shrubs in forest ecosystems [8, 77-79), had not been practically mentioned in the world literature as an economically significant pest [16, 80], however, in recent years, in Europe it has become a serious pest of fruit trees (apple trees, pears) [79, 81]. Unlike many other pentatomids, this species obligately overwinters at the nymphal stage [79]. A noticeable increase in its population density in the Republic of Chuvashia and in Perm City in 2019 is likely to be associated with a softening of the overwintering conditions, which contributes to an increase in the survival rate of overwintering nymphs [82, 83].

An outbreak of mass reproduction of *P. rufipes* was also noted by us under the conditions of Belgorod Province in 2020. In summer, adults of this species were often found along the edges of woodlands on the leaves of the box elder (*Acer negundo* L.) and blackthorn berries (*Prunus spinosa* L.), which were significantly damaged by autumn. The mass reproduction of *P. rufipes* can be judged by the fact that, in various places on shady forest roads and trails, many dead adults of this species were noted in early September: their average number was about 4 specimen/m^2, but in some places it was 6-8 times higher. The reason for such a high death rate among adults remained unknown; only a few specimens out of hundreds collected were affected by the entomoparasitic fungus *Beauveria bassiana* s.l. (Ascomycota: Hypocreales: Cordycipitaceae) (B.A. Borisov, unpublished data).

A similar example is the species *Antiteuchus innocens* Engleman et Rolston, common in Central America, which had not previously considered a serious pest [84, 85], but in recent years, an increased population densities of this species have been recorded in the pine forests of Mexico; this lead to the weakening of trees [86]. The reasons for the increase of the abundance of *A. innocens* have not been identified yet.

As noted above, the most important factor in the appearance of phytophagous insects in new regions is the increasing intensification of transport (cars, by sea, railways, and air) due to which phytophagous pest can be inadvertently transported hundreds and thousands of kilometers. Then they have a chance to successfully establish and adapt to the local climate and vegetation, which are new to them, and to build up their populations. In the absence of natural enemies (predators, parasites, pathogens), outbreaks of mass reproduction and expansion of the invasive area often occur [62]. This way, *N. viridula* and *H. halys*, as well as many other pentatomid species, continue to spread around the world [28, 44, 87].

Brachynema germarii (Kolenati) is widely distributed from the Canary Islands and Mediterranean countries through Transcaucasia and Asian deserts to Mongolia and Northern China [4, 16]. In 2017, this species was discovered in Transbaikalia (Daurian State Nature Reserve) and in the south of Krasnoyarsk Krai [88], and in 2020 — in the Voronezh State Natural Biosphere Reserve [89]. It is assumed that this pentatomid could get to the south of Krasnoyarsk Krai with the personal belongings of air passengers from neighboring Tyva, and to Voronezh Province independently, as a result of natural spreading in the north-west direction under conditions of abnormally hot weather.

The mottled shield bug *Rhaphigaster nebulosa* (Poda) is widely distributed in central, southern and southeastern Europe, in the Caucasus and Transcaucasia, Kazakhstan, Turkey, Iran, Pakistan, Asia, and North Africa [4]. During the last two decades, there have been reports of expanding of the range of this species to the north in different parts of Europe [90, 91]. In Russia, until recently, *R. nebulosa* had never been found in Voronezh Province, however, in 2010-2020, 73 specimens of this bug were collected in the region along with five specimens of its obligate parasite − tachinid fly *Cylindromyia bicolor* (Olivier) (Diptera: Tachinidae) [92].

In recent years, the East Asian (Malaysia, Thailand, Cambodia, Vietnam, Laos, southern China, and Japan) polyphagous yellow-spotted stink bug *Erthesina fullo* (Thunberg) has made long-distance movements. Since 2017, it has been repeatedly found in Albania [93], and since November 2020 — in Brazil, near the port city of Santos [94]. The bug is dangerous for citrus fruits, pears, persimmons, common jujube (*Zizyphus jujuba* Mill.), Ceylon cinnamon tree (*Cinnamomum verum* J. Presl), pine trees (*Pinus* spp.) and other plants [95]. If this species manages to naturalize in the countries of southern Europe, then there is a risk of its invasion into the territory of Russia and acclimatization at least in the south of its European part.

Among pentatomids, the polyphagous African stink bug *Bagrada hilaris* (Burmeister), which came to the USA about 15 years ago, and later to Mexico, Chile and India, is also of concern. It is known to damage cabbage and other crops of the *Brassicaceae* family [96]. In Europe, it has already been recorded on Malta and on the Italian island of Pantelleria [97]. The species poses a great threat to the countries of the Mediterranean basin [97], and later to the southern regions of Russia.

Thus, it is possible to identify several of the most likely causes leading to the expansion of ranges, increase in population density, and harmfulness of pentatomids. First of all, this is the global climate change (most significantly, warming), which in many cases contributes to an increase in the number of generations realized during the growing season, expanding opportunities to adapt to conditions of higher latitudes, often contributing to an increase in insects' fecundity. Other reasons include polyphagous nature of pentatomids, their high migration ability at

the adult stage, unintentional introduction as a result of the intensification of transportation of various goods and the development of tourism, the absence of natural enemies (predators, parasites, pathogens) in the recipient regions, low coordination of quarantine and plant protection systems. An urgent issue for further research and practice of plant protection is the development of measures for effective control of pest populations which pose a particular threat to crops, but at the same time have a high population density in natural ecosystems.

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