

Biology, Ecology, and Management of Rednecked Peanutworm (Lepidoptera: Gelechiidae)

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Abstract

The rednecked peanutworm, *Stegasta bosqueella* (Chambers), is the main lepidopteran pest in South and Central American peanut fields. The species name was misspelled earlier in the literature and the incorrect name is still more cited. In this review, we revisit the history of *S. bosqueella* classification. Although the rednecked peanutworm is an important defoliator in some peanut producing countries, there is scarce information on some aspects of the biology as well as plant response to this insect species. Economic threshold levels are not yet well established and, consequently, decision making is compromised. Chemical control is the main tool used to control larval infestations. Moreover, some studies on host plant resistance, biological control, and attract-and-kill strategy were conducted to control the rednecked peanutworm. These tactics were promising and could be useful to enhance a peanut integrated pest management program. We present here a review of *S. bosqueella* life history, biology, ecology, and management options as well as needs for enhancing the current control strategies.

Key words: *Stegasta bosqueella*, *Arachis hypogaea*, Peanut IPM, groundnut pests, lepidopteran defoliator

Stegasta bosqueella was first described by Chambers in 1875 as *Oecophora bosqueella* using a specimen from Texas (Chambers 1875a). Chambers described the species in the genus *Oecophora* by mistake but rectified his error almost immediately. The original description was published in May of 1875, in which Chambers inserted the species *basqueella* (note that the species name was mistakenly written but was corrected later; details below) into genus *Oecophora* (Family Tineidae). However, two months later (July 1875), the author changed the description of the genus to *Gelechia*, family Gelechiidae (Chambers 1875b).

Walsingham (1882) argued against Chambers' original description and mentioned that the described individual certainly belonged to the genus *Gelechia* and not to the *Oecophora*. This author also mentioned that the palps and the shape of the posterior wings can be used to distinguish both genera *Gelechia* and *Oecophora* and suggested that the description should be changed as follows: 'Brownish brown head; the upper or lower part of the pale orange fascia is dyed white; both the costal points are white, the outside being bigger and more visible; there is also a small white spot on the margin below the apex, with some white scales below it'. Furthermore, Meyrick (1917) included the species *bosqueella* in his original description of the genus *Stegasta*. Moreover, other synonyms are found for this species as follow: *Stegasta basquella*, *Parastega bosqueella*, *Parastega basqueella*, *Gelechia basqueella*, and *Gelechia costipunctella* (Möschler 1890, Walsingham 1897, Busck 1903, Meyrick 1904, Bondar 1928, Lee et al. 2009).

Considering the species name, Barber (1939) and Ferguson et al. (1991) noted much variation (i.e., *basqueella*, *bosqueella*, *bosquella*). In order to end this confusion, Hodges (1963) analyzed the occurrence and concluded that *Stegasta bosqueella* is the name to be used for the rednecked peanutworm. This author mentions that there was probably some confusion in the spelling of the original name, because Chambers (1875a,b) himself originally used *basqueella* and later used *bosquella* (Chambers 1878). Consequently, two new names were erroneously inserted in the literature. The original name is based on the name of Texas County, Bosque, and in the original description, Chambers incorrectly wrote that name as Basque. A scientific name, generic or original, based on the name of a person or a place, should be written similarly to the original. Thus, the correct spelling is 'bosque' instead of 'basque'. Moreover, a second point concerns the suffix 'ella'. In the order Lepidoptera, this suffix was used to designate members of the genus *Tineina* and was added to the first part of the name. The name *bosquella* might have probably been written to facilitate pronunciation. Thus, Chambers made an invalid adoption by changing the spelling of *bosqueella* to *bosquella*. Nevertheless, in the original description, there is no evidence of this fact (Chambers 1875a). In conclusion and above all, the name to be used is *Stegasta bosqueella* and not *Stegasta bosquella*.

Even nowadays (almost 150 yr after the first description, followed by the correction), there is still inconsistency in the correct spelling of the *S. bosqueella* species name. For instance, a search using the bibliographic search engine Google Scholar (from Google,

Inc.) as of April 2020 revealed that there were 206 scientific publications using *Stegasta bosquella*, whereas there were 105 articles using the correct name *Stegasta bosqueella* during the period from 1946 to 2020. Therefore, the incorrect name is more often utilized.

Origin and Distribution

The genus *Stegasta* is originally from the South American continent (Meyrick 1917). It occurs in several parts of the world and has been reported in the United States (Chambers 1875a), Mexico (Lee et al. 2009), Central and South America (Busck 1903, Landry and Roque-Albelo 2010, Meyrick 1917), Australia (Lower 1899, Meyrick 1904, Turner 1919), South-West Africa (Mey 2011), and North Korea (Bae et al. 2014). *Stegasta bosqueella* is a cosmopolitan species associated with peanut, *Arachis hypogaea* L., whose center of origin is South America (Gabriel 2016), but it is cultivated throughout the Americas.

Meyrick (1904) classified 15 species within the *Stegasta* genus. However, similar morphological characteristics that occur in this genus make identification laborious. So, caution is necessary to avoid errors in the documentation of *Stegasta* species. An example of incorrect identification occurred in Peru, where *S. bosqueella* was related as an insect-pest associated with peanut (Schmitz and Landry 2007). However, in later studies, it was found that the recorded pest in the country was actually *Stegasta zygotoma* Meyrick, 1917 (Lepidoptera: Gelechiidae) (Monzón Julián 2013). Furthermore, Wolcott (1948), when searching insects in Puerto Rico, reported that specimens of *S. bosqueella* can differ morphologically according to their location or region where they originate. According to this author, *S. bosqueella* is a widely distributed species and individuals in Puerto Rico are noticeably smaller than those in the United States and their coloration can vary.

Vergara (1976), who studied the morphology and biology of *Stegasta capitella* (Fabricius) (Lepidoptera: Gelechiidae), mentioned that *S. capitella* has white coloration of the head and thorax, whereas in *S. bosqueella* only the front of the head is partially white, and all the head and thorax are dark brown. Thus, the coloration of the head and thorax allows one to differentiate these two species.

In Brazil, *S. bosqueella* is the most important peanut lepidopterous pest due to its abundance and widespread occurrence in all peanut producing regions (Almeida 2015, Pinto 2018). The first reports of *S. bosqueella* in Brazil were recorded by Bondar (1928, 1930). This author described in detail the occurrence and identification of this species. Individuals collected in peanut fields were infesting the stems, tips and axils of the peanut leaves in large numbers (Bondar 1930). Also, in South America, *S. bosqueella* is the most important pest in peanuts in Ecuador and it generally appears ~3 wk after the crop is established (Coello Guin 2019). In North America, reports state that the rednecked peanutworm is the most common foliage-feeding larva in peanut fields but control is usually not necessary (Mulder and Berberet 2004, Vogt et al. 2001).

Description of Life Stages

Adult

The original morphological description of the adult of *S. bosqueella* by Chambers (1875a) was as follows: ‘Palpi dark brown, with a yellow white annulus around the middle and tip of the second and third joints. Head yellowish white; antennae dark brown, with the extreme tip of the basal joint white. Thorax above, and base of the forewings brown; dorsal margin of the forewings, from the base to the ciliae, pale orange yellow, with a broad fascia of the same hue

at about the basal fourth, passing across the wing and gradually narrowing to the costa. Behind this fascia to the apex the wing is brown, containing an irregular yellowish spot at about the middle of the costal margin, and a white one immediately before the ciliae. The brown-color has a rich maroon tint, and not a dead lustreless hue. Legs and tarsi brown, annulated with pale yellowish. Venter brown, with two yellowish bands before the apex’ (Fig. 1).

According to Manley (1961), the sexual dimorphism of the *S. bosqueella* species can be observed in adulthood. The differentiation between male and female is made by visualizing a median dorsal tuft of the scales at the apex of the abdomen (Fig. 2), which is present exclusively in males.

Egg

The eggs are small and ovoid-elongated in shape. They are initially white, but with the embryo development the color turns to pale-yellow or cream coloration. *Stegasta bosqueella* eggs measure ~0.30 mm in length and 0.20 mm in diameter. They are usually laid individually or in small groups in the plant stem, being fixed between the foliar trichomes (Fig. 3). Nevertheless, they do not attach strongly to the plant (Manley 1961, Pinto 2018).

The chorion surface presents a rough texture and shows a reduced number of aeropyles, which can help in the reduction of water loss and consequently egg desiccation (Fig. 4). This is the first accurate report of *S. bosqueella* egg structure although previous reports suggested that the chorion surface was smooth (Manley 1961).

Larva

The first technical description of the immature phase of *S. bosqueella* was performed by Dyar (1903) and was as follows: ‘Head rounded, bilobed, full, oblique and retracted, mouth projecting; the labium and spinneret prominent; clypeus high, triangular, antennae small; shining black, labium and epistomal pale; width, 0.6 mm. Body cylindrical, normal; joints 2 to 3 and 12 to 13 tapering; thoracic feet distinct, the joints black ringed; abdominal feet slender, rather small, normal, the crotchets in a complete ring about the small, circular planta; cervical shield large, transverse, rounded on the posterior corners, shining black, cut by a fine, faint, pale dorsal line; joints two and three entirely dark vinous except the neck in front of the cervical shield; joint 4 in the incisures in front and in a broad band on the posterior third of the same dark vinous, extending even on the venter. The white area thus formed on the anterior part of joint 4 on the otherwise uniformly red thorax appears irregularly edged and lumpy. Rest of the body whitish, immaculate, greenish from the blood, tubercles small, round, black but distinct, bearing short, stiff setae. On the thorax tubercles ia and ib, are separate, iia and iib, iv



Fig. 1. Adult of *Stegasta bosqueella* on a peanut plant.

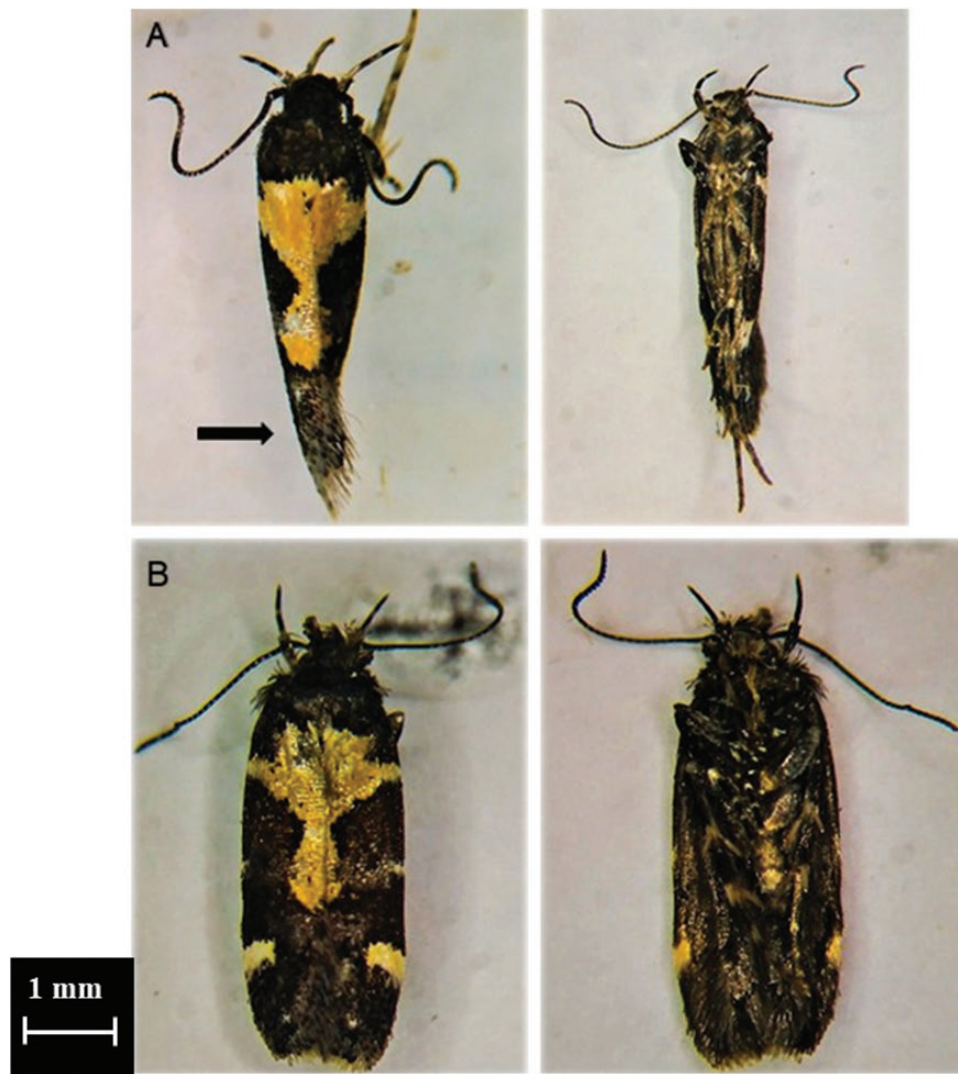


Fig. 2. Dorsal and ventral view of the male (A) and female (B) of *Stegasta bosqueella* (arrow indicates the dorsal tuft present exclusively in the male).



Fig. 3. *Stegasta bosqueella* eggs adhered to peanut plant petiole.

and v united in pairs. On joint 3 the tubercle plates are large of ib, plus f: ib and iv plus v, but on joint 3 they are small, and the paired tubercles stand separate through contiguous; on the prothorax; the prespiracular and subventral tubercles are large. On the abdomen tubercle *i* is dorsad and cephalad to ii, iii is near the spiracle, above it iv and v contiguous, in line, vi subventral posteriorly, *vii* of three contiguous tubercles on the anterior side of the leg base, vi on the inner side of the leg base. Spiracles small, black; ringed; anal shield pale brown. distinct; anal feet with brownish outer shields'.

The *S. bosqueella* larvae have five instars and are predominantly whitish. First-instar larvae range from 0.75 to 1.0 mm in length. At this stage, the pro and mesothorax are not reddish (Fig. 5A). They have a small black prothoracic shield, which is, in fact, present in all larval stages. In the second instar, the larvae are about 2-mm long and the reddish coloration of prothorax and mesothorax begins to be evident (Fig. 5B). In the third instar, the reddish coloration in the prothorax and mesothorax are clearly visible. The larvae measure about 3.5 mm in length and the predominant white color of the body becomes creamy (Fig. 5C). Individuals in the fourth (Fig. 5D) and fifth instars (Fig. 5E) show similar characteristics to those of the third instar, varying only in size, ca. 5 and 7 mm, respectively.

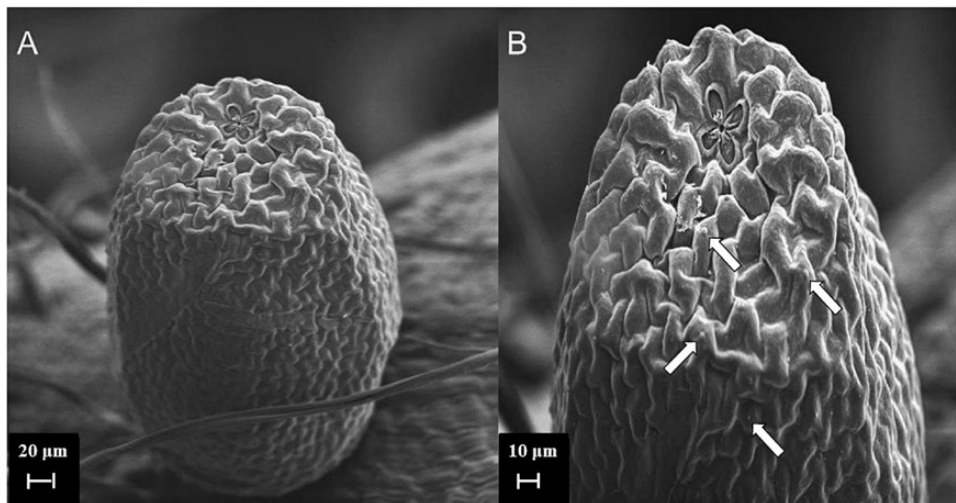


Fig. 4. *Stegasta bosqueella* egg photographed using scanning electron microscopy, in which reticulated chorion (A) and the presence of aeropile (indicated by arrows) (B) are observed.

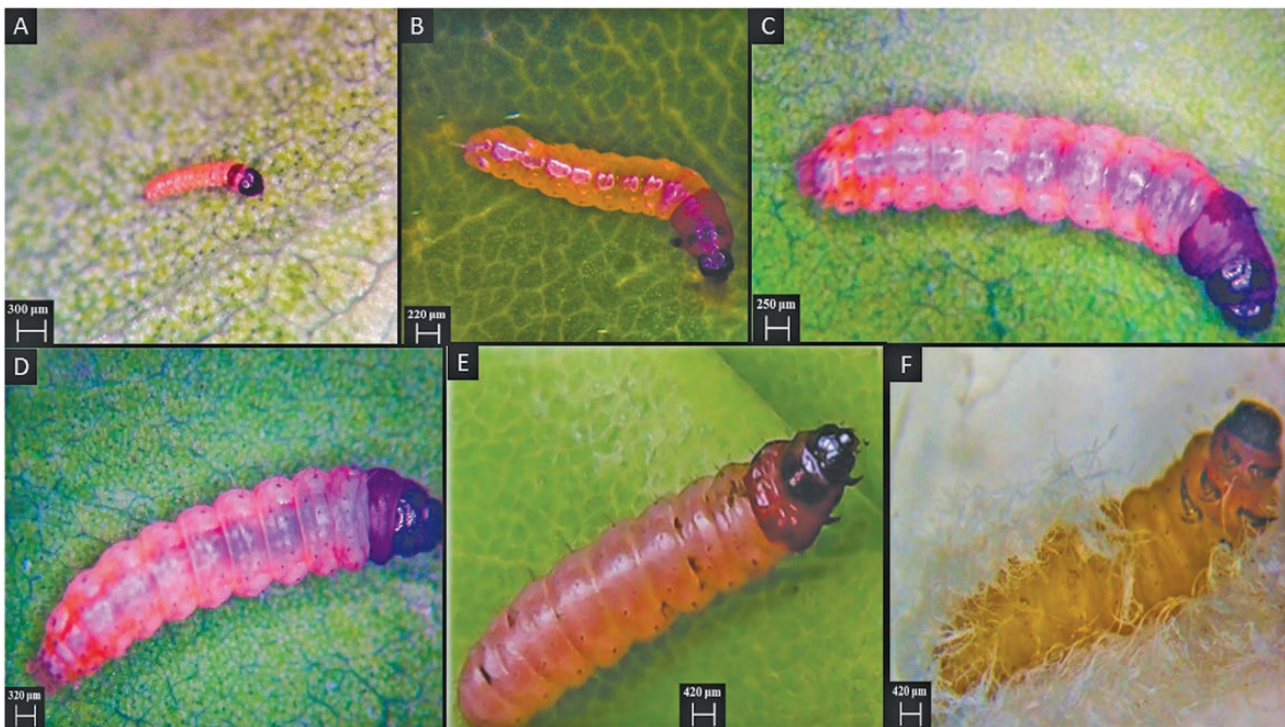


Fig. 5. *Stegasta bosqueella* larval development: first instar (A), second instar (B), third instar (C), fourth instar (D), fifth instar (E), and prepupa (F).

Pupa

At the prepupal stage, larvae stop feeding and begin to cover themselves with silk filaments, in which they are protected until reaching the pupal stage (Fig. 5F). According to Manley (1961), the pupal period mostly takes place in the soil, but in some cases, *S. bosqueella* larvae may pupate inside closed leaflets or in galleries formed in the axils of plants (Fig. 6). This was confirmed after scouting peanut fields during the 2017/2018 growing season in Brazil (J. R. L. P., personal observation). The pupae are 5–8 mm in length. The pupal coloration inside the silken cocoon varies gradually from light brown, observed at the moment that the larval integument is detached, to dark brown, prior to adult emergence (Fig. 7).

According to Boiça Junior et al. (2011), males and females can also be differentiated at the pupal stage. Males have the gonopore opening located medially in the terminal portion of the abdomen, whereas the females have this opening at the beginning of the terminal portion of the abdomen (Fig. 8).

Bioecological Aspects

Insect Biology

The life cycle stages of *S. bosqueella* (Fig. 9), determined in controlled conditions ($25 \pm 2^\circ\text{C}$, $60 \pm 10\%$ RH, and 12:12 [L:D] h), ranged from 2 to 3 d for egg, 8 to 15 d for larva, and 4 to 10 d for

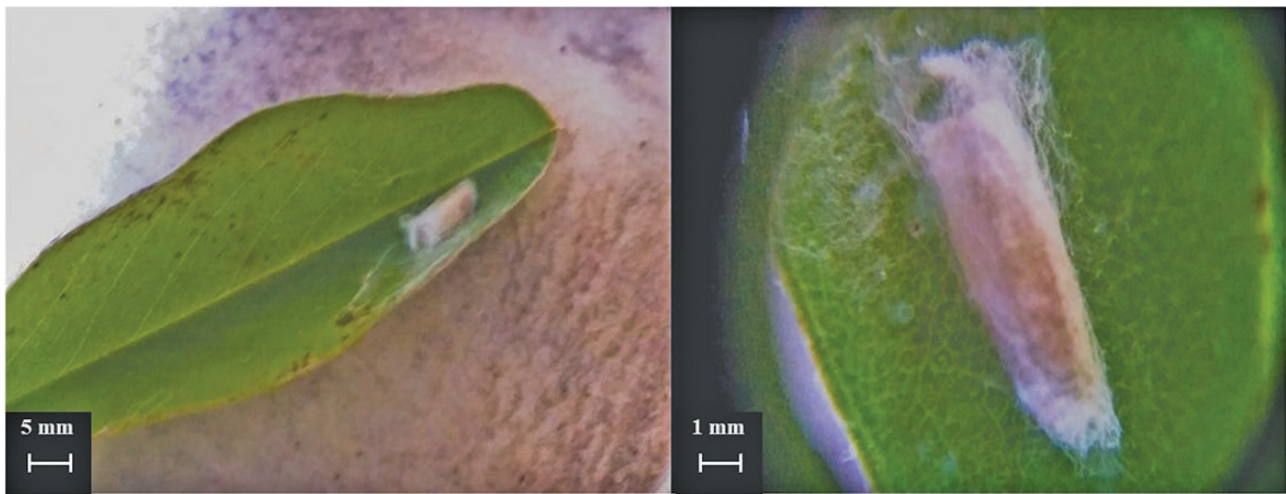


Fig. 6. *Stegasta bosqueella* larvae wrapped in silk cocoon.



Fig. 7. Dorsal and ventral view of the pupa of *Stegasta bosqueella*, shortly after its formation (A) and close to adult emergence (B).

pupa. Adult longevity varied from 6 to 17 d (J. R. L. P., personal observation). These values were similar to those found by Boiça Junior et al. (2011), who established *S. bosqueella* rearing techniques under the same controlled conditions and observed an average of 13.6 and 6.6 d for larval and pupal development, respectively. These authors also found an average longevity between 22.3 and 29.4 d for adults of *S. bosqueella* fed with honey water at 10% concentration. Survival of nonfed adults was only 3.8 d.

Eggs are laid singly or in small groups on the petiole or under the bracts of the peanut plant buds. Boiça Junior et al. (2011) determined that each properly fed female has the capacity to oviposit approximately 230 eggs. After hatching, the *S. bosqueella* larva moves toward the closed leaflets where it is sheltered.

The first- and second-instar larvae feed on the epidermal layer of the leaflets (Fig. 10). Older larvae may feed through the leaflets, leaving usually symmetrical feeding injury (holes). Upon completion of development, larvae usually seek shelter on the ground, where they will begin the pupation process.

Host Plants

The main host plant of *S. bosqueella* is peanut. However, this insect species has also been reported in other leguminous plants. Manley (1961) reported *S. bosqueella* in peanut, partridge pea (*Cassia fasciculata* Michx.), alfalfa (*Medicago sativa* L.), prairie acacia (*Acacia angustissima* Mill.), blue wild indigo (*Baptisia australis* L.), field pea (*Pisum arvense* L.), hairy vetch (*Vicia vilpula* Roth), cowpea (*Vigna sinensis* L.), soybean (*Glycine max* L.), and kudzu (*Pueraria thumbergiana* Benth) in Oklahoma. According to the author, it is likely that one or more generations will develop on alfalfa and partridge pea before peanut plants are available in the area.

Other plant species have also been cited as hosts of *S. bosqueella*. Dyar (1903) found rednecked peanutworm in plants of *Cassia chamaecrista* L. (Fabaceae) in the United States and D'Araújo e Silva et al. (1967) reported this insect in the axils of pineapple leaves (*Ananas comosus* [L.] Bromeliaceae) in Brazil. Also, this species was reported on the flower buds of *Zornia* spp. and *Stylosanthes* spp. (Fabaceae) damaging the seeds especially in drier periods, which correspond to the flowering season in South

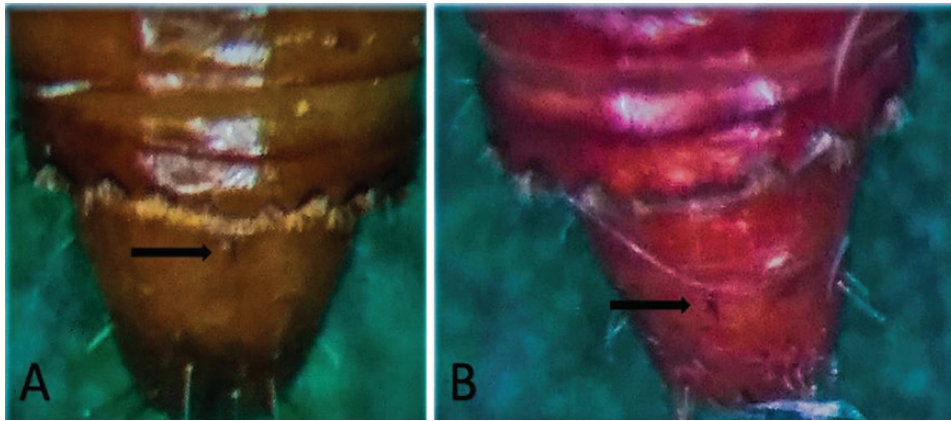


Fig. 8. Terminal portion of the pupae of *Stegasta bosqueella* evidencing the position of the opening of the gonopore. Arrows indicate the opening at the beginning of the terminal portion of the female abdomen (A) and the gonopoid opening located medially at the male (B).

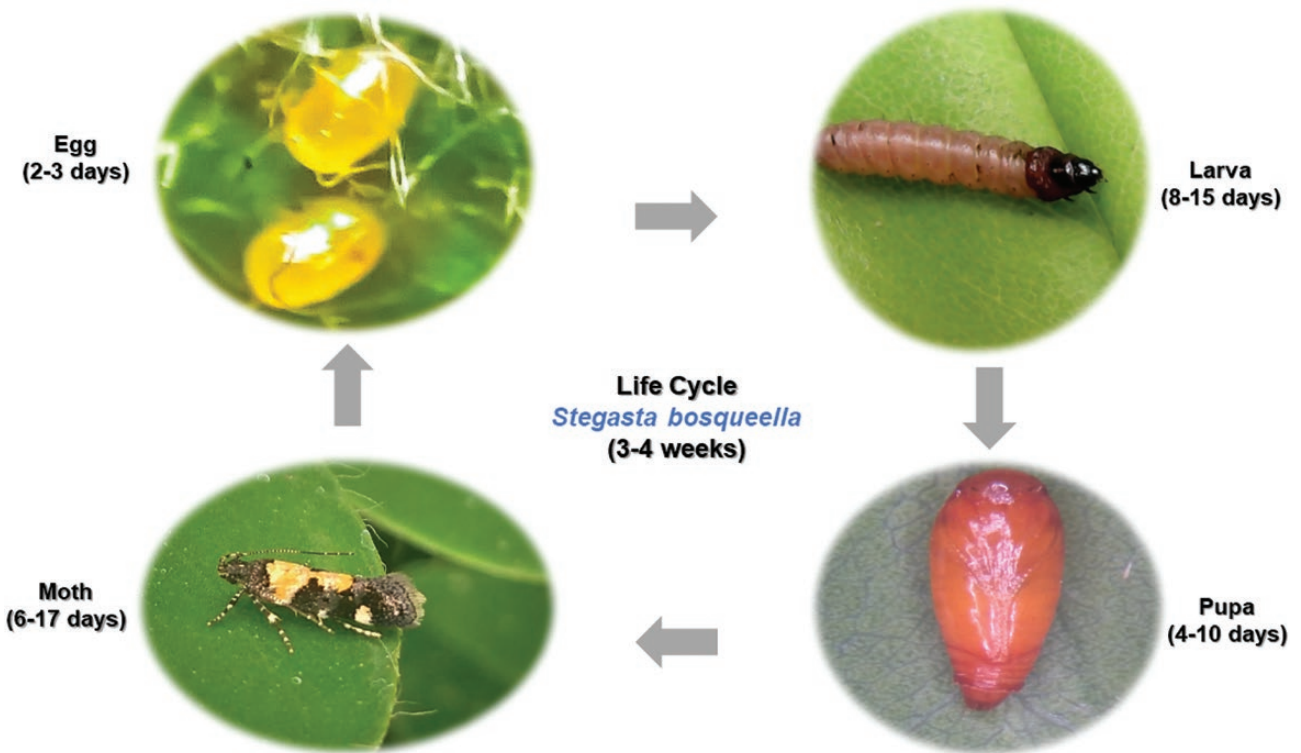


Fig. 9. Life cycle of *Stegasta bosqueella*.

America (Calderón and Arango 1985). Bissell (1942) reported a low infestation of *S. bosqueella* larvae in peanut in the state of Georgia in the United States. This author noted that the larvae entered through the ends of the folded leaves but did not cause significant damage. Also, *S. bosqueella* larvae were collected in *C. chamaecrista* in the same region and in other localities of the state. Ferguson et al. (1991) found larvae in *Kuhnistera pinnata* (Walter) (Fabaceae) (= *Petalostemon corymbosus* Michx.) as well as several other plants of the Fabaceae family.

The above reports indicate that *S. bosqueella* is mostly associated with leguminous plants. However, in an eventual absence of these hosts, this insect species can utilize plants of other botanical families as food resource.

Injury

The rednecked peanutworm can be found on peanut fields throughout vegetative and reproductive plant stages. However, the critical period of *S. bosqueella* larval occurrence in peanuts is from plant emergence to 70 d of the crop cycle (Almeida 2015). Nogueira et al. (2016) reported that the highest larval infestations of *S. bosqueella* occur between 53 and 67 d after plant emergence during pod development.

Stegasta bosqueella larvae causes a characteristic injury to peanuts. Larvae feed on young, unfolded leaflets (Fig. 11), causing symmetrical perforations (Fig. 12) upon leaf expansion. In some cases, such injury prevents the leaflets from opening, elongating the vegetative growth of the plant (Almeida 2005). They can also feed and



Fig. 10. Peanut leaflet with injury caused by first-instar larva of *Stegasta bosqueella*.

destroy meristematic tissues (buds) affecting the production of new shoots, pegs, and pods, and reducing the overall development of plants (Wall and Berberet 1979, Suassuna et al. 2014), leading to a potential yield loss when population densities are high (Wall and Berberet 1979).

Despite the rednecked peanutworm abundance in peanut, plant response to *S. bosqueella* injury is not well understood. Peanuts may present certain levels of tolerance to defoliation similarly to the response reported for other leguminous plants (Higley 1992). Thus, studies to better understand the mechanisms by which herbivory caused by *S. bosqueella* modify physically and physiologically peanut plants as well as how it affects the growth and yield of this crop are very important.

Consequently, understanding how insect injury impacts yield loss is essential for the development of the economic injury level (EIL) and economic threshold (ET). These concepts are essential for integrated pest management (IPM). Knowing the population density of *S. bosqueella* capable of causing economic damage to peanut will result in more appropriate recommendations for managing this pest.

Management of the Rednecked Peanutworm

Sampling Immature Stages

Due to the habit of being hidden inside the leaflets during the larval stage, sampling of *S. bosqueella* larvae in peanut should be carried



Fig. 11. Peanut leaflets damaged by feeding of *Stegasta bosqueella*.



Fig. 12. Symmetric lesions in the peanut leaflets resulting from the larval feeding of *Stegasta bosqueella*.

out by opening the leaflets of the plants. Almeida (2015) recommends a zig-zag sampling to ensure the best representation of the field and to record the number of insects in a sampling sheet or other device. The distribution of *S. bosqueella* larvae in peanut crops occurs randomly (Boiça Neto 2016). Therefore, the sampling effort to scout the insect pest should not be as high as if it were clumped. Information of the abundance of insects will allow one to identify the critical period (time of high infestation of the pest). As fields are usually evaluated once per week, frequency of scouting can be increased or reduced depending on pest occurrence. For peanuts, 50 plants should be randomly sampled in areas up to 10 ha (Almeida 2015). Larger crop areas should be divided into small plots (≤ 10 ha) and sampled individually.

In addition, Suassuna et al. (2014) recommend starting sampling 15 d after plant emergence, recording both insect pest and diseases at each sampling point. One should select 10 sampling points per plot, three consecutive plants in a row per sampling point, and four closed leaflets (one leaf) at random per plant for a total of 120 leaflets per plot.

Sequential sampling is another sampling methodology that can be used. This approach is characterized by using a nonfixed number of samples (Young and Young 1998) in contrast to the fixed sample size described above. For the implementation of *S. bosqueella* larval sequential sampling, Boiça Neto (2016) described that the peanut farmer must adopt some practices including division of the field into smaller plots (preferably ≤ 10 ha). This will provide a greater precision in pest population assessment and decision making. According to the author, a minimum of 9 samples (sample = one plant) should be taken before starting to compare the accumulated number of *S. bosqueella* larvae scouted to a preestimated number to assure the population is below (stop sampling and no control) or above (stop sampling and recommend control) the threshold level.

The choice between the sampling methods to be adopted should be based on the scout level of knowledge and operational cost benefit,

as there are advantages and disadvantages in both methodologies. Sequential sampling is a great tool when the situation of time saving and reduced sampling cost is the goal. However, the mathematical complexity and the lack of information about the economic injury level for *S. bosqueella* damage regarding the use of this strategy are limiting factors for the adoption by peanut producers. The ongoing improvement of digital agriculture which includes algorithms established in digital spreadsheets associated with smartphones or other electronic devices will be essential to optimize insect pest sampling in order to simplify data collection and decision making by producers.

Sampling Adults

Because sampling the immature stage is extremely laborious and is probably the main reason for low adoption among peanut farmers, Pinto (2018) described the use of a food attractant based on oleoresin and sugar in combination with delta traps as an efficient method for monitoring *S. bosqueella* in commercial peanut farms. This method allows the evaluation of in-field adult abundance. Similarly, the use of sugarcane molasse-based bait added to traps made from plastic bottles was also reported to attract adults of *S. bosqueella* (Rivero et al. 2017). Therefore, the use of food attractant can be useful to enhance the efficacy of trapping as a sexual pheromone for *S. bosqueella* is not yet available. However, a better understanding of population dynamics of adults and its relationship with immature stages is necessary for enhancing decision making.

Control Methods

Studies on feeding injury caused by *S. bosqueella* on peanut plants are limited. Therefore, recommendations for *S. bosqueella* control differs according to production sites. In Brazil, *S. bosqueella* control generally occurs based on the experience of a technician during the cropping season and there are two main recommendations. One, as reported by Godoy et al. (2014), suggests that the control should be performed if larvae are observed in 20% of sampled leaflets. The second recommendation is to start control when an average of one plant is infested with one larva of *S. bosqueella* or any other lepidopterous defoliator (Fernandes 2019).

In Ecuador, Elena (2012) indicates that decision making for *S. bosqueella* control varies depending on the vegetative development stage of peanuts. Therefore, control is recommended when 10, 30, 45, and 65% of the leaflets are infested with live *S. bosqueella* larvae at 20, 40, 60, and 80 d after emergence (DAE), respectively. In total, ten leaflets should be observed per sampling site prior to making this decision. In the United States, Mulder and Berberet (2004) stated that insecticide applications for *S. bosqueella* larval control should only occur when population density is high (i.e., 80–100% of infested leaflets) or if these infestations occur in combination with other larval defoliators such as *Spodoptera* spp. Otherwise insecticide applications are not necessary. Abbott et al. (2019) suggest that control of defoliating insects in peanut in the United States is economically viable only when defoliation exceeds 5% at 80 DAE.

Chemical Control

Chemical insecticides have been the primary and is still the main control method used against *S. bosqueella* (Bondar 1930, Brandão Filho 1943, Arthur et al. 1959, Walton and Matlock 1959, López 1991, Hartwich et al. 2007, Castro and Ramón 2015, Abbott et al. 2019).

A wide range of insecticides were evaluated in the main peanut producing regions in North, Central and South America to manage *S. bosqueella* larva (Carvalho et al. 1968, Lara et al. 1970, Berberet 1978, Lopez 1991, Scarpellini et al. 2013, Almeida 2015). In these studies, the following insecticide groups were predominantly used: pyrethroids, neonicotinoids, organophosphates, and carbamates.

However, contact insecticides are not very efficient due to larval habits of feeding in closed peanut leaflets. Thus, broad-spectrum systemic insecticides are commonly used (Almeida 2015). Unfortunately, these insecticides have a detrimental impact on natural enemies essential in an IPM program (Wanumen et al. 2016).

The availability of active ingredients (and commercial products) used to *S. bosqueella* control, varies tremendously in different peanut producing countries (Table 1). Considering the major peanut producers in the Western Hemisphere (United States, Argentina, and Brazil) which comprised 83.9% of the planted area in the Americas (FAO 2020), we can notice that the availability of compounds with different modes of action, based on IRAC (2020), is much greater in the United States than in the other countries (Table 1).

This scarcity of registered products represents an obstacle to the establishment of insecticide resistance management (IRM) strategies, as chances of cross-resistance within a family of structurally related insecticides can be increased. Moreover, in Brazil, IPM in peanut is not yet fully adopted by peanut growers and insecticides are applied without knowledge of insect damage potential or regard for optimum application timing. Thus, peanut growers spend resources applying various insecticides while growing the crop.

In the United States, as previously discussed, *S. bosqueella* is considered occasional or minor pest and chemical control was only recommended when damage is excessive (Alabama Cooperative Extension System 2020). With regard to Argentina, high populations of *S. bosqueella* have not been observed; furthermore, other insect pests are not relevant (Bongiovanni et al. 2012). Therefore, the limitation of registered products has not been a problem. In Central America and some South American countries, it was noticeable that growers are still relying on broad-spectrum insecticides or are shifting to botanical insecticides, such as azadirachtin (Elena 2012)

Even with the predominance of the use of chemical control as a strategy for *S. bosqueella* management in the peanut crop, some studies were developed in the areas of plant resistance, biological control and attract-and-kill strategy. The use of these strategies can bring advances to provide the farmer additional tools to control this insect.

Plant Resistance

As previously discussed, due to *S. bosqueella* larval feeding and sheltering habits, the insecticides used for its control must have special features (e.g., systemic or translaminar products), which may make this control more costly. Thus, the search for resistant plant genotypes to *S. bosqueella* is of great importance for the development of breeding programs, aiming to develop new resistant peanut materials. Consequently, this control strategy can greatly reduce pesticide use and its drawbacks.

Wild species of the genus *Arachis* have been studied for their resistance to pests and diseases (Subrahmanyam 1983, Stalker and Moss 1987, Michelotto et al. 2015, Srinivasan et al. 2018). In Brazil, research involving the development of resistant peanut materials aimed mostly at evaluating disease resistance (Fávero et al. 2009). Few studies have been developed to obtain *S. bosqueella* resistant peanut cultivars (Janini 2011) and most of them are commonly used

Table 1. Registered insecticides (chemical, biological, or other) and mode of actions available for the rednecked peanutworm control in the major peanut producing countries in the Americas (sources: Crop Data Management Systems, Inc., for the United States [CDMS 2020], AGROFIT (MAPA 2020) for Brazil, CASAFE (2020) for Argentina

Main group and primary site of action	Subgroup or exemplifying active ingredient	Active ingredients	EUA	Argentina	Brazil
	A-Carbamates	Carbaryl	●		
1	B-Organophosphates	Acephate	●		●
1	B-Organophosphates	Chlorpyrifos	●		
1	B-Organophosphates	Profenofos			●
3	A-Pyrethroids Pyrethrins	Lambda-Cyhalothrin	●		●
3	A-Pyrethroids Pyrethrins	Cypermethrin	●		●
3	A-Pyrethroids Pyrethrins	Deltamethrin		●	●
3	A-Pyrethroids Pyrethrins	Bifenthrin, Gamma-Cyhalothrin, Zeta Cypermethrin, Cyfluthrin, Esfenvalerate	●	●	
3	A-Pyrethroids Pyrethrins	Beta-Cyfluthrin	●		●
4	A-Neonicotinoids	Thiamethoxam			●
4	A-Neonicotinoids	Imidacloprid	●		●
5	Spinosyns	Spinosad, Spinetoram	●		
6	Avermectins	Abamectin		●	
13	Pyrroles	Chlorfenapyr			●
15	Benzoylureas	Diflubenzuron	●		●
18	Diacylhydrazines	Methoxyfenozide	●		
22	A-Oxadiazines	Indoxacarb	●		
28	Diamides	Chlorantraniliprole, Flubendiamide	●	●	
UN		Azadirachtin			
UNB*		<i>Chromobacterium subsusgae</i> strain PRAA4-1t and spent fermentation media	●		
Total commercial products registered			91	14	28
Targeted physiology					
Nerve and muscle					
Respiration					
Growth and development					
UN –Compounds of unknown or uncertain MOA					
UNB—Bacterial agents (non-Bt) of unknown or uncertain MOA					

to analyze resistance into available commercial materials (Di Bello et al. 2015, Nogueira et al. 2016). This trend is because most of the Brazilian commercial varieties are extremely susceptible to fungal diseases and require large amounts of fungicide sprays during the peanut crop growing season.

In other South American countries, such as Ecuador, researchers are also developing breeding programs with materials that have higher pest resistance to increase productivity and profitability, because commonly used genotypes are susceptible to *S. bosqueella* injury (Guamán Jiménez, et al. 2014, Coello Guin 2019). Differently, breeding programs in Argentina have focused on disease and water stress tolerance because problems with insect pests are not relevant (Soave et al. 2011, Fernandez and Giayetto 2017).

In North America, breeding programs focus on increasing tolerance to pests and diseases (Stalker and Moss 1987, Srinivasan et al. 2018). To accomplish such goals, alleles that confer resistance to pests and diseases obtained from wild *Arachis* species were inserted into peanut commercial materials (Simpson and Starr 2001, Mallikarjuna et al. 2011). Interestingly, these studies did not evaluate the resistance of peanut genotypes to *S. bosqueella* defoliation.

In view of this, it is known that peanut plants that even present constitutively low resistance to insect pests can reduce 10–35% in losses compared to a susceptible material. However, moderate-resistant plants can show 35–65% reduction in damage, whereas a plant with high resistance will achieve reduction >65% (Campbell and Wynne 1980). Some studies sought to evaluate the resistance of wild peanut species (*Arachis* spp.) to *S. bosqueella* attack and as a result it was found that the genotypes V13985 (*A. hoehnei*), V13670 (*A. stenosperma*), KG30076XV14167 (*A. ipaensis* × *A. duranensis*), W421 (*A. stenosperma*), LM5 (*A. stenosperma*), V7639 (*A. kuhlmannii*), V9243 (*A. kuhlmannii*), W11291 (*A. krapovickasii*), V13571 (*A. microsperma*), and V9010 (*A. stenosperma*) are resistant to *S. bosqueella*. Antixenosis, antibiosis and tolerance were identified as mechanisms for the host plant resistance in these genotypes (Janini 2009). As the expression of genetic characteristics is affected by temporal and spatial variations in the environment, bioecological characteristics of the insect-species as well as of the plant genotypes, the resistance levels are determined using a relative scale. For this, the genotypes are compared with a susceptible control (i.e., the most injured genotype) and to genotypes with known pre-established levels of resistance under the same experimental conditions (Smith 2005).

Resistance of plants can be divided into three categories: antixenosis, antibiosis, and tolerance (Painter 1951). Thus, studies describing each mechanism of resistance to *S. bosqueella* larvae will be described below.

Antixenosis

Antixenosis, also known as nonpreference, refers to a mechanism by which a plant affects the behavior of herbivores impeding herbivory or reducing their colonization. Janini (2011) evaluated these mechanisms on wild species (*Arachis helodes*, *A. kempff-mercadoidi*, *A. kuhlmannii*, *A. stenosperma*, *A. villosa*, *A. magna*, *A. vallsii*, *A. cardenasii*), amphidiploid (*A. gregoryi* × *A. linearifolia*), and commercial peanut cultivars (IAC Runner 886 – *A. hypogaea*) for the attractiveness of third-instar *S. bosqueella* larvae. No-choice and choice tests showed that the amphidiploid *Arachis gregoryi* × *Arachis linearifolia* was the least preferred for *S. bosqueella* larvae. Therefore, they can be selected for crossings with commercial materials to help enhance more productive and insect resistance genotypes.

Conversely, the commercial material IAC Runner 886 presented high levels of preference and consumption by *S. bosqueella* larvae

(Janini 2011). Similar results were also obtained by Di Bello et al. (2015) for the same variety as well as for other commercial cultivars such as IAC 147, IAC 125, and IAC 503 (*A. hypogaea*). These materials did not present resistance in the antixenosis category. Thus, we can conclude that the current cultivated materials in Brazil are still susceptible to *S. bosqueella* and other important lepidopterous pests, such as *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), for which commercial peanut cultivars showed no resistance in the antixenosis category (Campos et al. 2010).

Antibiosis

Antibiosis is a type of resistance in which the plant affects the biology of an herbivore. Janini (2011) carried out a study using the same wild species, amphidiploid and peanut cultivars evaluated for antixenosis (see above). The author noted that the wild genotypes V 7635 (*A. vallsii*) and V 7639 (*A. kuhlmannii*) prolonged the rednecked peanutworm cycle, causing reduced pupal weight and reduced larval and pupal viability. In addition, the wild genotype V 7635 caused total insect mortality avoiding the emergence of adults. In contrast, as verified in the antixenosis category, the commercial cultivar IAC Runner 886 did not affect *S. bosqueella* larval development.

Furthermore, evaluating the response of peanut cultivars of upright (IAC Tatu, IAC 22, IAC 8112, and IAC 5) and runner growth habits (IAC runner 886, IAC 147, IAC 125, and IAC 503) to *S. bosqueella*, Di Bello et al. (2015) concluded that the cultivars IAC 22 and IAC 8112 affect larval viability. However, these upright and runner growth cultivars did not influence other biological parameters such as pupal weight, sex ratio, and longevity of *S. bosqueella* larvae (Di Bello et al. 2015). When evaluating the development of *S. bosqueella* larvae on commercial peanut cultivars, Di Bello (2019) found that none of the evaluated cultivars showed resistance in antibiosis category, being IAC 503 considered moderately resistant; IAC Runner 886 and IAC Caiapó susceptible and Granoleico and IAC OL3 highly susceptible.

Tolerance

Tolerance is the plant's ability to support or recover from the damage caused by an insect population, without affecting their biology or behavior. Differing from antibiosis and antixenosis which are associated with metabolic cost of plants due to the resistance mechanism (Karban 2011), tolerance reduces the negative effects of herbivores with no or reduced metabolic costs associated with plant development and yield (Painter 1951, Smith 2005, Stout 2013). Moreover, tolerance does not affect behavior and development of the insect pests. This is important to avoid any selection pressure on pest populations and greatly reduces chances of pest resistance development (Peterson et al. 2017). Few studies have attempted to evaluate tolerance of wild species, amphidiploids and peanut cultivars to the injury of *S. bosqueella*. Janini (2011) carried out field trials during two growing seasons and observed that the wild accession V 7639 (*A. kuhlmannii*) stood out for its higher seed production and lower yield losses compared to the control treatment. Thus, these materials have the potential to be crossed with commercial cultivars to incorporate pest resistance.

The exploitation of wild peanut germplasm (*Arachis* spp.) seems to be an interesting strategy to find genes of interest to enhance resistance of cultivars to *S. bosqueella*. However, wild materials which present greater resistance to insect pests are often associated with undesirable agronomic characteristics such as catenate fruits or low yield (Singh et al. 1991). The main obstacle is the variability

in *Arachis* wild species, since most are diploid, while the cultivated species are allotetraploid. Thus, the ploidy barrier makes the hybrids obtained from these crossings sterile (Godoy 2011). Due to these characteristics, studies on wild peanut species are laborious and time consuming, making peanut breeding programs difficult.

Application of molecular biology techniques, such as sequencing and molecular markers, can significantly increase the potential of peanut breeding programs and develop new possibilities for selecting progenies with high levels of insect resistance and other desirable agronomic traits for the development of commercial peanut cultivars (Stalker 2017). For example, Paula et al. (2017) used reproductive, molecular, and morphological characterizations to evaluate the genome and genetic similarity of wild species of peanut. The authors were able to explain the irregular meiosis presented in peanuts diploid hybrids and found amphidiploid materials that could be used in breeding programs to develop new peanut cultivars with pest resistance to the rednecked peanutworm.

Biological Control

Biological control studies on peanut have mainly focused on surveys of natural enemies associated with *S. bosqueella* (Table 2). In North America, parasitoids belonging to the family Braconidae, Chalcididae, Perilampidae and Ichneumonidae (Hymenoptera) were observed (Manley 1961, Wall and Berberet 1975, Grissell and Schauff 1981, Yu et al. 2019). In addition to these parasitoids, ants of the species *Solenopsis invicta* (Buren) (Hymenoptera: Formicidae) have also been reported as predators of *S. bosqueella* larvae (Vogt et al. 2001). Other natural enemies have also been observed in the United States peanut crop and may contribute to the biological control of peanut pests, including the minute pirate bug, *Orius insidiosus* (Say) (Hemiptera: Anthocoridae); the big-eyed bugs *Geocoris punctipes* (Say) and *Geocoris uliginosus* (Say) (Hemiptera: Lygaeidae); the damsel bugs, *Nabis* spp. (Hemiptera: Nabidae) (Kharboutli and Mack 1993); and beetles belonging to the family Staphylinidae, Anthicidae, and Carabidae and the earwig *Labidura riparia* (Pallas) (Dermaptera: Labiduridae) (Kharboutli and Mack 1993).

In South America, larval parasitoids of the Braconidae and Ichneumonidae families were observed (Janini et al. 2010, Pinto 2018). Particularly in Brazil, there are numerous reports of biological control success by egg parasitoids in many crops, such as sugarcane and soybean, constituting an economically viable and less environmentally disruptive method of control (Parra and Coelho 2019). Egg parasitoids are widely used in inundative biological control for eliminating the pest before damage is caused to the crop (Wajnberg et al. 2008). However, for peanut crop, research related to biological control is still limited and there is no biological control program currently recommended for peanut pests. In this context, the parasitism of the egg parasitoids *Telenomus remus* Nixon (Hymenoptera: Scelionidae) and *Trichogramma pretiosum* (Hymenoptera: Trichogrammatidae) were evaluated on *S. bosqueella* eggs, but no parasitism was recorded (Pinto and Fernandes 2020). Thus, considering the importance of the rednecked peanutworm in peanut and the widely used of egg parasitoids for lepidopterans pest control in several countries (Van Lenteren et al. 2018), other biological control agents or strains should be evaluated on *S. bosqueella* eggs in order to establish basis for the biological control of this important pest.

Furthermore, entomopathogens can be included as important biological control agents. In Peru, Segura-Contreras and Carbajal-Villaverde (2018) found significant larval mortality with the application of different *Beauveria bassiana* concentrations against *Stegasta* sp. larvae under laboratory conditions. Moreover, the use of *Bacillus thuringiensis* was previously recorded in United States (Berberet 1978) and Ecuador (Guamán Jiménez et al. 2014), but its use has not been widely adopted in peanut producing areas. Thus, additional studies seeking to evaluate the efficiency of entomopathogen-based products including virus such as *Baculovirus* which are widely used around the world (Kalha et al. 2014) should also be evaluated in the control of *S. bosqueella* larvae.

Attract-and-Kill Strategy

The management of *S. bosqueella* in peanut cultivation for several years depended on the application of insecticides, which usually targets the immature stages with the use of broad-spectrum insecticidal

Table 2. Natural enemies associated with *Stegasta bosqueella*

Order	Family	Species	Reference
Hymenoptera	Braconidae	<i>Habrobracon gelechia</i> , <i>Microplitis croceipes</i>	Yu et al. (2019)
		<i>Chelonus</i> spp.	Wall and Berberet (1975), Janini et al. (2010)
		<i>Apanteles epinotiae</i>	Manley (1961)
		<i>Macrocentrus ancylivora</i> , <i>Orgilus</i> spp., <i>Diadegma compressum</i> , <i>Pristomerus spinator</i>	Wall and Berberet (1975)
		<i>Bassus</i> sp.	Pinto (2018)
	Ichneumonidae	<i>Diaparsis</i> sp.	Pinto (2018)
		Chalcididae	<i>Psilochalcis deceptor</i> , <i>Psilochalcis mirabilis</i> , <i>Psilochalcis threa</i>
	<i>Invreia mirabilis</i>		
	<i>Invreia usta</i> , <i>Invreia threa</i>		Grissell and Schauff (1981)
	Perilampidae	Formicidae	<i>Perilampus fulvicornis</i>
<i>Solenopsis invicta</i>			Vogt et al. (2001)
<i>Orius insidiosus</i>			Kharboutli and Mack (1993)
Hemiptera	Anthocoridae	<i>Orius insidiosus</i>	Kharboutli and Mack (1993)
	Geocoridae	<i>Geocoris punctipes</i> , <i>Geocoris uliginosus</i>	Kharboutli and Mack (1993)
Nabidae	Nabidae	<i>Nabis</i> spp.	Kharboutli and Mack (1993)
		<i>Nabis</i> spp.	Kharboutli and Mack (1993)
Dermaptera	Labiduridae	<i>Labidura riparia</i>	Kharboutli and Mack (1993)
Coleoptera	Staphylinidae	-	Kharboutli and Mack (1993)
	Anthicidae	-	Kharboutli and Mack (1993)
	Carabidae	-	Kharboutli and Mack (1993)

roducts. However, the pursuit of more selective control technologies within the scope of IPM is necessary (Way and van Emden 2000). Behavioral manipulation of insect pests through semiochemicals is more environmentally friendly method of control and can fit very well in an IPM program (Foster and Harris 1997). An approach to be adopted using semiochemicals is called attract-and-kill strategy. This technique aims at attracting adults to a source containing insecticide in its composition. This attraction assures the contact between insect and insecticide, increasing the chances of control and consequently reducing the number of insects in the next generation (Charmillot et al. 2000). An advantage of this strategy is the restriction of contact between a toxic substance and the crop, beneficial organisms, or the environment (Gregg et al. 2018).

The use of the attract-and-kill strategy has been extensively explored in the control of important pests such as the Codling moth, *Cydia pomonella* (Linnaeus) (Lepidoptera: Tortricidae) (Lösel et al. 2000), the Mediterranean fruit fly *Ceratitidis capitata* (Wiedemann) (Diptera: Tephritidae) (Navarro-Llopis et al. 2013), and the Brown marmorated stink bug *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (Morrison et al. 2016). Pinto (2018) evaluated the use of attract-and-kill strategy for *S. bosqueella* adult control in a commercial peanut area and observed that the applications interfered in the population dynamics of adults. For this purpose, a food attractive composed by oleoresins and sugars was combined with the insecticide methomyl, in 4% of the evaluated commercial product concentration. The use of this carbamate insecticide is recommended because it causes high and fast mortality of adults at low concentrations (Gregg et al. 2016). Consequently, a reduction of 70.37 and 62.07% *S. bosqueella* adults captured in the traps was observed when the application was performed after the observation of an increased abundance of adults caught in peanut commercial fields.

Therefore, the use of food attractant added to insecticide as bait to control *S. bosqueella* adult moths in the peanut crop can be a very advantageous strategy. Due to the attraction, the food bait enhances the contact between insect and insecticide and reduces the overall amount of insecticide applied against *S. bosqueella*, because the application is performed only on one or few crop rows.

Conclusions

It is estimated that 20–30% of the peanut crop production costs are associated with chemical control of the main insect pests and diseases in most of the peanut producing regions of North and Latin America (Garcia-Casellas 2004, Michelotto et al. 2015). For this reason, there is a huge demand for new alternatives to increase productivity as well as to reduce yield losses and production costs. Chemical control with broad-spectrum insecticides has been the main control method against *S. bosqueella* infestations. However, there are other prospective tools that can be used for *S. bosqueella* management on peanut crop such as applied biological control, plant resistance and attract-and-kill strategies. In addition to these tactics, the development of disease-tolerant peanut materials can help enhance insect pest management, because the application of fungicides will be reduced. The need of disease control using fungicides on a regular fashion obliges peanut growers to additionally control insect pest through tank mix of products. Therefore, the application of pesticides is usually calendarized, without considering insect pest population.

Furthermore, studies to better understand the population dynamics of *S. bosqueella* and peanut response to injury caused by this insect are necessary. This information is required for enhancing *S. bosqueella* sampling programs and threshold levels on peanut

crop as well as to form the basis for decision making in an IPM strategy. Peanut response to peanut insect defoliation is still not well established. However, future studies may consider not only the red-necked peanutworm, but also other lepidopterous defoliators, since *S. bosqueella* is not the only lepidopterous associated to this crop.

Finally, the technological development observed in peanut production (e.g., development of new cultivars, yield loss reduction during mechanized harvesting, and improvement of the postharvest process) has contributed to increasing productivity. However, advances are still needed in the mechanized harvesting process to decrease the number of peanut stubble plants that remain in the field as a source of insect pests and host for phytopathogens. Additionally, sustainable production systems with higher quality of food and nonpersistent chemicals are demanded by consumers worldwide. Therefore, the establishment of EILs and ETs is necessary for *S. bosqueella* in an IPM program. Based on experiences in other crops, these thresholds are key elements to optimize decision making and, consequently, the management of the rednecked peanutworm population with minimal economic and ecological impacts.

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