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REVIEW ARTICLE

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The American cocoa pod borer, *Carmenta foraseminis*, an emerging pest of cocoa: A review

El barrenador americano de la mazorca de cacao, *Carmenta foraseminis*, una plaga emergente del cacao: una revisión

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Abstract

1. This review provides a synthesis of the available knowledge on *Carmenta foraseminis*, an emerging cocoa pest in northern South America.
2. This moth was first described in 1995 in Panama, and its proliferation across the Amazon basin is currently threatening the production of cocoa in the region and may endanger the sector's sustainability. Hence, it is important to further draw the attention of researchers towards this emerging pest. The larvae of this lepidopteran burrow within the pod and feed on beans and their pulp, causing important losses.
3. We present a critical synthesis of the knowledge on *C. foraseminis* (biology, geographic distribution, phylogenetic status, ecology), to identify the cause of its emergence and key points for its control.
4. We also describe similarities to another lepidopteran, the Cocoa Pod Borer (CPB) *Conopomorpha cramerella*, which is the main pest of cocoa in Asia, especially on the way it is controlled and eventual lessons and recommendations that can be drawn from the situation in Asia to better understand and manage cocoa pod infestation in the Amazon basin.
5. Additionally, we propose further research themes to be explored for *Carmenta foraseminis* that will help in the development of efficient management practices.

KEYWORDS
Amazon, forest, insect pest, Sesiidae, *Theobroma cacao*

INTRODUCTION

The deleterious impact of pests and diseases on global cocoa production is a significant concern, with an estimated loss of 30%–40% of potential yield globally (Flood et al., 2004; Ploetz, 2016). This impact varies across

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A Spanish translation is available in the Supporting Information online.

continents due to the presence of different pests and diseases, diverse environmental conditions, plant species/varieties, socio-economic factors and technological levels (Oliveira et al., 2014). Furthermore, the extent of yield and quality losses varies depending on the specific plant organ(s) affected and the severity of damage inflicted. These losses can be categorized as primary or secondary, contingent upon whether the reduction in yield (and quality) is observable in the epidemic year or subsequent years (Avelino et al., 2018; Zadoks & Schein, 1979). While estimating primary losses caused by organisms directly affecting fruit development is relatively straightforward, accurately quantifying secondary losses resulting from pests and diseases impacting tree production capacity is challenging due to intricate interactions with tree physiology. Consequently, there remains a significant gap in research pertaining to the precise estimation of secondary losses, warranting further investigation to enhance our understanding and management strategies in cocoa production systems.

While cocoa pests and diseases are ubiquitous across cocoa-growing regions, their incidence and impact vary considerably. Intriguingly, it appears that in Africa and Asia, cocoa is more susceptible to pest pressures, whereas in the Americas—cocoa's continent of origin—diseases hold greater significance (Bagny-Beilhe et al., 2018). For instance, in West Africa, mirid bugs (*Sahlbergella singularis* Haglund (1895)) pose a significant threat to cocoa, causing production losses ranging from 25% to 40% due to their ability to feed on cocoa pods and shoots (Yede et al., 2012).

Cocoa pod borers (CPB), notably *Conopomorpha cramerella* (Snellen) (Lepidoptera: Gracillariidae), are significant pests present across all three primary cocoa-producing continents—America, Africa and Asia. However, they emerged as a major threat primarily in Asia. Cocoa pod borer infestations in Asia result in substantial primary losses annually, as they feed on the pod placenta, disrupting bean development and compromising bean quality (Beevor et al., 1993; Day, 1989; Lim, 1992). Severe infestations can lead to local cocoa yield reductions ranging from 60% to 84%, with economic losses that reached up to US$40 million annually in Indonesia by 2000 (ICCO, 2016). Smallholders, with limited resources for control, typically experience losses between 20% and 50%. Between 2008 and 2012, cocoa production in the East New Britain Province of Papua New Guinea plummeted by 80% due to CPB impact, resulting in widespread abandonment of cocoa cultivation among farmers (European Union External Action, 2015). Recognizing the gravity of CPB's adverse effects on cocoa production, numerous researchers have endeavoured to devise effective management strategies. Frequent harvesting, destruction of ripe pods and husks to thwart pupation in the field and targeted spraying of resting sites with deltamethrin, cypermethrin or lindane emerged as the most efficacious control methods against CPB (Mumford & Ho, 1988). However, certain insecticides, such as lindane, are forbidden for use on cocoa by the EU.

In contrast, within the Americas, particularly in the Amazon basin—cocoa's native habitat—pathogen pressure emerges as the predominant challenge hindering cocoa production. Key diseases in the region include frosty pod rot (caused by *Moniliophthora roreri*, Cif.), witches' broom disease (caused by *Moniliophthora perniciosa*, Stahel) and black pod rot (primarily caused by *Phytophthora palmivora*, E.J. Butler). The deleterious impact of these diseases on both quantity and quality of production has resulted in the abandonment of entire cocoa cultivation areas (Correa Álvarez et al., 2014; Rice & Greenberg, 2000). However, a potential new threat is emerging in the Americas. Since the mid-1990s and early 2000s, *Carmenta foraseminis* (Eichlin) (Lepidoptera: Sesiidae), known locally as 'Mazorquero' in Peru and 'Carmenta Negra' in Colombia, has surfaced as a significant cocoa pest in this region. *C. foraseminis* is particularly prevalent in Venezuela, Colombia and Peru, exacerbating cocoa losses due to its direct impact on cocoa pods. *C. foraseminis* develops from egg to adult on cacao pods. Larvae penetrate the mesocarp, feed on the mucilage and perforate the seeds (Delgado et al., 2023). *C. foramseminis* can also produce significant indirect damages by creating openings that facilitate infection by microorganisms. Given the parallels in life traits between *Carmenta foraseminis* and *Conopomorpha cramerella*, along with the latter's significance as a cocoa pest in Asia, it is prudent to closely monitor the expansion of the pod borer in the Amazonian basin. Coupled with the impact of frosty pod rot and witches' broom, this new pest could pose a genuine threat to cocoa cultivation and productivity in this region. Despite its potential destructive capacity, this pest has received relatively scant attention to date. This systematic literature review aims to consolidate current knowledge pertinent to the biology, geographic distribution, effect on cocoa production and control of *Carmenta foraseminis* and offers recommendations for further research efforts.

Systematic literature review

In the pre-2000 literature, *C. foraseminis* (Eichlin, 1995) and its counterpart *C. theobromae* (Busck, 1910) are frequently treated interchangeably. Thus, during the review process, we independently used '*Carmenta foraseminis*' and '*Carmenta theobromae*' to look for sources on Google Scholar and Web of Science (WOS) with the option 'All database'. These two online platforms complement each other: WOS primarily indexes academic articles published by commercial publishers, while Google Scholar encompasses both academic and grey literature, such as theses, documents and reports that have not undergone formal peer review (Haddaway et al., 2015).

Grey literature, as defined by the Luxembourg convention, encompasses 'information produced and distributed on all levels of government, academics, business and industry in electronic and print formats not controlled by commercial publishing, that is where publishing is not the primary activity of the producing body' (Third International Conference on Grey Literature, 1997). While grey literature utilization is more prevalent in health sciences compared to agricultural sciences, its significance in systematic reviews is widely acknowledged. Consequently, international organizations have incorporated guidelines and manuals advocating for its inclusion in review and meta-analysis processes. We purposefully incorporated grey literature into our review, recognizing its potential as a valuable source of recent research across disciplines. Moreover, grey literature is often available online more readily than other publication types (Haddaway et al., 2015).

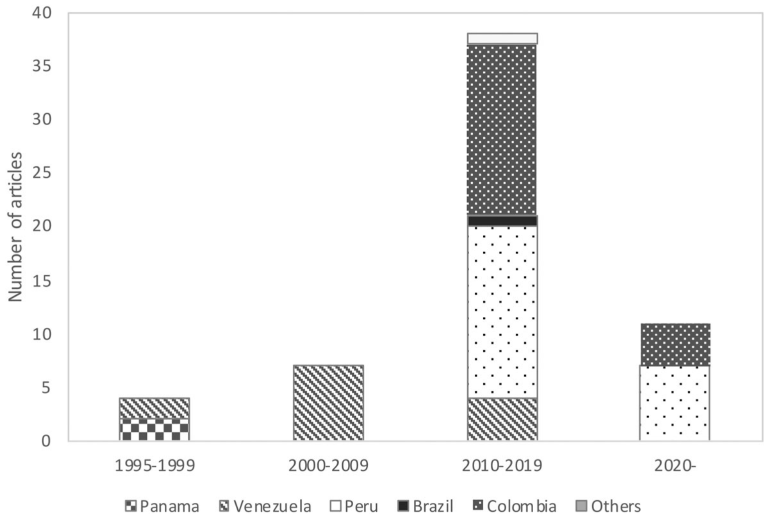

FIGURE 1 Number of articles considered by the review according to their date of publication and country of origin. When papers do not deal with a particular national setting, they are classified as 'Others'.

During our search phase, we considered all scientific articles, theses, conference proceedings and books, while excluding citations and slideshows. Full articles were retrieved from available databases, including governmental institutions' databases and national universities' repositories. Articles that remained inaccessible even after consulting authors were excluded from the analysis. An informal review process assessed the relevance of each article based on adherence to protocols, statistical rigour and authors' affiliations (with preference given to authors affiliated with universities, research institutes, and national or international research institutions). To ensure comprehensiveness, we scrutinized the bibliography of each article. The systematic literature review (SLR) protocol was conducted on 15 December 2023. We obtained 11 + 11 results on Web of Science (searching in All Database) and 100 + 53 results on Google Scholar for *C. theobromae* and *C. foraseminis*, respectively. However, after applying exclusion criteria and removing duplicates, only 60 relevant documents remained. Notably, there has been a noticeable increase in attention towards *C. foraseminis* over the past two decades, reflected in the growing number of publications on the subject (Figure 1). A substantial portion of the gathered documents (32%) constituted grey literature, predominantly authored by academics and graduate research students.

OVERVIEW OF CURRENT KNOWLEDGE ON AMERICAN COCOA POD BORER

Biology

Taxonomic position

Carmenta foraseminis is a clearwing moth, member of the Sesiidae family (Boisduval, 1829) within the Lepidoptera order. The Sesiidae family is a diverse group encompassing 149 genera, 1352 species and 48 subspecies (Pühringer & Kallies, 2004). Known for its xylophagous larvae, many Sesiidae species inflict damage on agricultural crops by boring into live wood, including stems, branches and roots, in diverse hosts that range from shrubs to trees (Harms & Aiello, 1995). Research within this family has predominantly focused on the damage caused by larvae of the *Synanthedon* genus, such as *S. myopaeformis*, known to be invasive in North America. *Synanthedon* larvae create galleries under the bark of fruit trees, particularly targeting old trees with damaged trunks, which can lead to the eventual demise of the tree (Bergh & Leskey, 2003). These larvae commonly infest multiple fruit varieties, including apples, as well as ornamental and nut trees found in both northern and southern temperate zones.

Conversely, *Carmenta* species are predominantly associated with tropical and subtropical regions, where they have been used or proposed as biocontrol of several invasive plant species given their high host specificity (Cordo et al., 1995). Examples of biocontrol include *C. mimosa* that feeds on *Mimosa pigra* (Forno et al., 1991; Ostermeyer, 2000; Paynter, 2005) and *C.* sp. nr *ithacae* feeding on *Parthenium hysterophorus* (Dhileepan et al., 2012), both in Australia. *Carmenta chromolaenae* has been proposed as a biocontrol of *Chromolaena odorata* in South Africa (Eichlin et al., 2009), while *Carmenta haematica* has been proposed as a biocontrol for *Gutierrezia* sp. in the United States (Cordo et al., 1995). However, *Carmenta* species have also been reported as pests of economically valuable crops. For instance, *C. chrysophanes* causes important production losses on persimmons (*Diospyros kaki*) in Australia (Vickers & Rumbo, 2001), while *C. theobromae* garners significant attention due to its negative impact on guava production in Colombia (Carabalí Muñoz et al., 2015; Deantonio Florido & Carabalí Muñoz, 2021; Pulido Blanco et al., 2021).

Currently, two *Carmenta* species have been reported feeding on cocoa trees. Reports dating back to 1957 in Colombia have documented *C. theobromae* attacking cocoa, primarily by creating galleries within cocoa pods. The other species is *C. foraseminis*, first described by Eichlin in 1995 and earned its name 'foraseminis' due to its unique

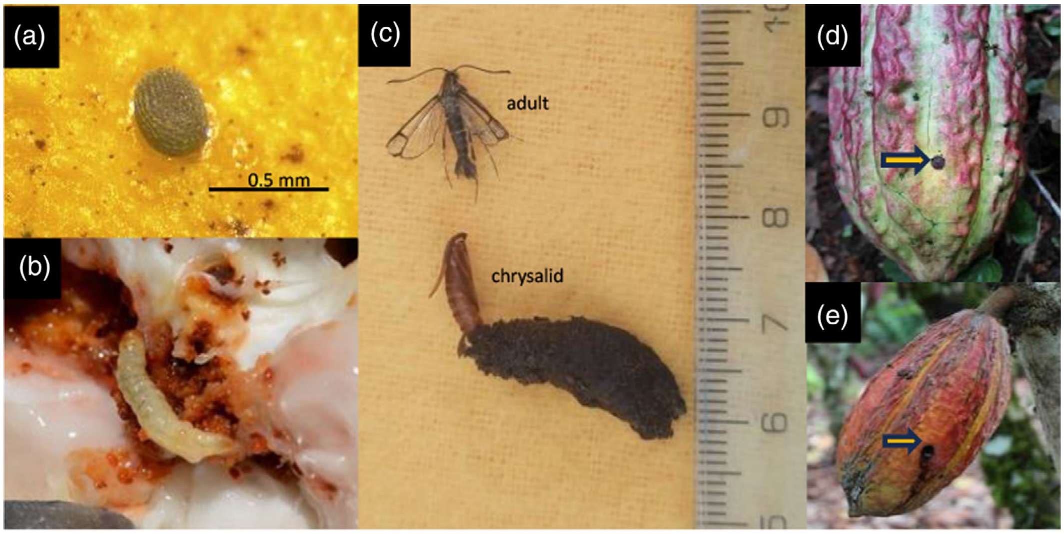

FIGURE 2 Life cycle of *C. foraseminis*. Eggs (a) are laid on the pod surface and larvae enter the fruit blocking the entry hole (d). 1. Once the larvae have fed, mostly on the mucilage surrounding the cocoa beans (b), they pupate inside the pod (c. shows a chrysalid extracted from a pod). Adults (as the male in c) leave the pod through an exit hole (larger than the entry hole), which is often clearly distinguishable by the presence of exudates (e). In (c), units are in centimetres.

ability to perforate the seeds it feeds on, a behaviour that is uncommon within the *Carmenta* genus (Harms & Aiello, 1995). Both *C. theobromae* and *C. foraseminis* belong to a complex of closely related species, including notably *C. guyanensis* and *C. surinamensis*. Morphological distinctions were primarily observed in male genitalia structure (Eichlin, 1995). A preliminary phylogeny of the *Carmenta* genus based on mitochondrial COI indicates a close genetic proximity between *C. foraseminis* (Colombian specimens), *C. surinamensis* (from Panama or French Guiana) and *C. guyanensis* (French Guiana specimen) (Taft & Cognato, 2017).

In 1986, extensive damage inflicted by lepidopteran larvae of the Aegerridae family and *Synanthedon* genus was reported on cocoa seeds in cocoa fields south of Lake Marago, Venezuela (Briceño Vergara, 1986). These larvae moved to the endocarp and consumed the fruit pulp surrounding the seeds. While it remains unclear whether the species mentioned in this study belonged to *Synanthedon* or *Carmenta* genera (likely *C. foraseminis*), this is considered the earliest documented instance of significant seed damage caused by lepidopteran larvae in Latin America. In this review, we focus on *C. foraseminis*, recognizing potential confusion in the literature predating 1995.

Morphology

Carmenta foraseminis undergoes complete metamorphosis in four distinct stages: egg, larva, pupa, and adult (Figure 2). A comprehensive description of each developmental stage has been proposed, complementing existing literature (Eichlin, 1995; Puchi, 2005), particularly based on laboratory-reared specimens in Venezuela (Puchi, 2005).

Adult *C. foraseminis* exhibit dark brown-black clearwing moth morphology with two thin yellow streaks on the thorax, presumably mimicking wasps (Figure 2c). Their abdomen features brown-black colouring with narrow yellow transverse dorsal stripes bordering the segments. Light yellow or white scales cover the abdominal sternum, predominantly on segments 4–7, and variably on other segments. The fifth segment has the widest fringe. Males can be distinguished from females by the presence of a tuft of apical scales on the abdomen and short, fine hairs along the entire inner edge of the antennae. Males are smaller in size (length: 1.78 ± 0.08 cm, width: 1.06 ± 0.06 cm) compared to females, with females being longer and wider (length: 1.98 ± 0.08 cm, width: 1.02 ± 0.05 cm). Both sexes possess wings approximately 8–9 mm in length (Puchi, 2005).

Carmenta foraseminis eggs are generally ovoid (Figure 2a), with dimensions of 3.63 ± 0.15 mm in length, 2.31 ± 0.10 mm in width and 1.57 ± 0.02 mm in height (Puchi, 2005). The eggs exhibit a reddish-brown chorion with a slight fissure in the micropyle area. Dorsally, they are distinctly light-coloured with longitudinal dotted stripes.

The larvae of *C. foraseminis* (Figure 2b) possess a whitish or light yellowish body adorned with black dots and hairs along their back. Their head exhibits a brown coloration and is slightly narrower than the pronotum. Notably, the pronotum features a pair of brown sclerotic bands, positioned distinctly from each other at the mid-posterior base. The inner edge of these bands gradually narrows from the base towards the apex (Puchi, 2005).

The pupa (Figure 2c) measures approximately 1.43 ± 0.04 cm in length and 0.33 ± 0.04 cm in width. It exhibits a light brown coloration. Notably, the pronotum features deep circular orifices, while the wing grooves are wide along their entire length. In frontal view, at the apex of the abdomen, the lateral and ventral spines appear almost fused, positioned close together, whereas the dorsal apex of the abdomen appears with four regularly spaced, flattened, sclerotized and clearly defined spines (Puchi, 2005).

TABLE 1 Life cycle durations (in days) according to available observations.

Source	Conditions/localization	Egg	Larva	Pupa	Adult	Total
Vivas et al. (2005)	Laboratory, Venezuela	8 ± 0.12	47.66 ± 10.13	11.7 ± 1.2	1.35 ± 1.31	74.71 ± 12.64
Alcantara Veliz (2013)	Field, Peru	8.0 ± 0.3	55.0 ± 0.5	14.0 ± 0.5	4.0 ± 0.4	81 ± 2
Cubillos (2013)	Unspecified, summary of different unpublished studies, Colombia	7	36	21	2–7	71
Luna Quispe (2019)	Laboratory (temperature 28°C and relative humidity 80%), Peru	7–8	30–35	21–22	6–7	64–73
Senejoa Lizcano (2015) cited by Caraballí Muñoz et al. (2018)	Laboratory (24.5 ± 2°C; RH 70 ± 5%; 12:12 LD), Colombia	6.62 ± 0.17	32.62 ± 0.21	12.32 ± 0.09	5.04 ± 0.14	56,65
Cabezas et al. (2017)	Field, Peru	7	30–36	14–21	3–8	54–72

Life cycle

Eggs of *C. foraseminis* are typically laid on the surface of cocoa pods, with a preference for pods aged between 2.5 and 3.5 months (Carabalí Muñoz et al., 2018; Cubillos, 2016; Sánchez & Herrera, 2005). Although it is generally assumed that only one egg is deposited per fruit (Cubillos, 2016), studies confirming this assumption are lacking. This contrasts with the several *C. theobromae* eggs and larvae to be found on guava trunks (Deantonio Florido & Carabalí Muñoz, 2021). Under laboratory conditions, eggs require approximately 7 to 8 days to hatch (Table 1). Upon hatching, the larva, which exhibits photophobic behaviour, immediately seeks refuge from light by burrowing into the cocoa pod. Once inside, it primarily feeds on the placental tissue of the fruit and the mucilage of the seeds; the larva of *C. foraseminis* may occasionally perforate the seeds themselves (Cubillos, 2013).

Carmenta foraseminis undergoes nine instars over a period ranging from 30 to 55 days (Table 1). Upon reaching the prepupa stage, the larva continues feeding on the mesocarp, eventually burrowing an exit hole (0.5–0.7 cm in diameter) and constructing a cocoon of faeces beneath the fruit epidermis. This cocoon serves to protect the pupa until the adult emerges (Carabalí Muñoz et al., 2018; Sánchez & Herrera, 2005). Externally, the fruit epidermis exhibits a rather small circular spot with colouration ranging from light to dark brown, depending on the plant genotype, serving as the most evident symptom of pest presence within the pod (Figure 2d). The pupal stage persists for a duration ranging between 11.7 and 22 days (Table 1).

The lifespan of the adult stage of *C. foraseminis* is relatively short, typically lasting between 2 to 7 days. The total duration of the life cycle varies, ranging from 54 days (reported in Tingo Maria, Huanuco, Cabezas et al., 2017) to 81 ± 2 days (reported in Satipo, Junin, Alcantara Veliz, 2013), with both reports stemming from field conditions in Peru (Table 1). Discrepancies in reported life cycle durations in the literature likely stem from variations in climatic conditions (such as temperature, relative humidity and elevation) both in the field and laboratory, as well as differences in food availability.

Based on an average cycle duration of 68 days, it can be estimated that there are between four to five generations of *C. foraseminis* per year. However, it is important to note that adult emergence rates vary significantly between studies, ranging from 75% to 21%, depending on the experimental conditions. For instance, in Venezuela, a higher adult emergence rate (75.6%) was observed in field conditions compared to laboratory conditions (42.3%) (maintained at temperatures of 28–33°C, relative humidity of 40%–65%, with a photoperiod of 12:12). Conversely, in Colombia, 40% of adults were obtained under controlled laboratory conditions, contrasting with emergence rates of 21%–24% under field conditions at 23°C and 75% RH (Cubillos, 2016).

The emergence of adults of *C. foraseminis* may depend on photophase. Under laboratory conditions (28 ± 5°C, 70 ± 15% RH, 12:12) in Venezuela, *C. foraseminis* begins to emerge between 6:00 AM and 7:00 AM (Herrera et al., 2012), but there was a greater emergence of adults in the afternoon around 1:00 PM (between 60% and 63.4%). Actually, adults show diurnal activity patterns, contrary to farmers' beliefs. In fact, the rarity of adult sightings in the field have led to the assumption that *C. foraseminis* adults exhibit nocturnal activity patterns.

The sex ratio ♂:♀, favouring females, typically ranges from 0.73:1 to 0.91:1 under laboratory conditions in Venezuela (del Sánchez et al., 2011), whereas it tends to be more balanced at 1:1 under controlled conditions in Colombia (Cubillos, 2016). In terms of reproductive activities, the calling behaviour of female *C. foraseminis* follows a bimodal pattern, characterized by two peaks of activity: one occurring from 10:00 AM to 11:00 AM and another from 4:00 PM to 5:00 PM. During this phase, males exhibit more intense flight and wing movements, while females remain relatively immobile with their abdomen curved. Subsequently, females extend their abdominal hair and engage in small jumps, presumably to release sex pheromones. In *C. theobromae*, the composition of extracts obtained from the females' abdominal extremity revealed two main compounds: Z,E-3,13-octadecadienyl acetate (Z,E-3,13-18:Ac) and Z,E-3,13-octadecadien-1-ol (Z,E- 3,13-18:OH) (Morillo et al., 2009). These findings hold promise for identifying and synthesizing sexual pheromones in the closely related species, *C. foraseminis*, which could be employed to trap males in cocoa fields.

Enhanced understanding of the biology and ecology of this pest is imperative for refining control strategies. For instance, the number of eggs a female can lay during its lifespan remains uncertain, as well as the optimal climatic conditions for each stage of the cycle under the

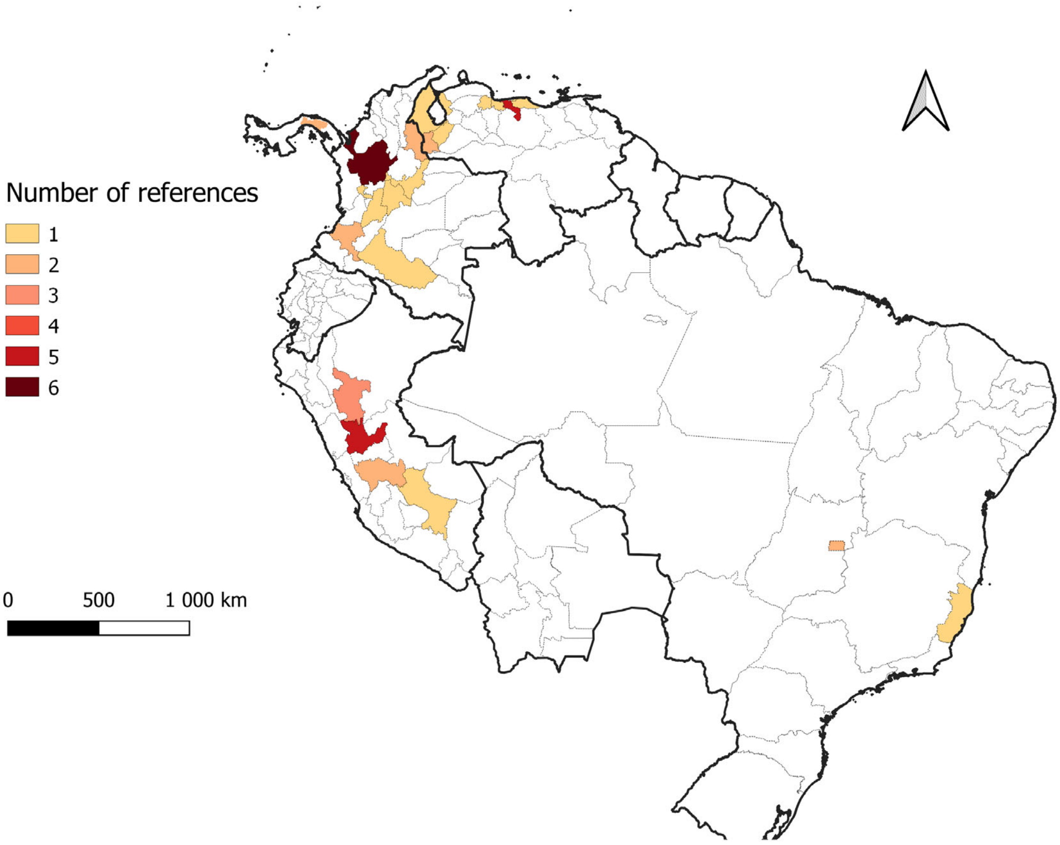

FIGURE 3 Map of the states where the presence of *C. foraseminis* has been registered in literature. Sources below.

same controlled conditions. Determining this life trait would offer insights into the optimal target stage for effective control strategies.

Hosts

Carmenta foraseminis appears to have relatively recently adopted cocoa as a host plant. Its natural hosts belong to the Lecythidaceae family and include species such as *Gustavia angustifolia*, *G. superba* and *Eschweilera* sp. (Eichlin, 1995). These species are native to the tropical forests of Central and South America, spanning regions such as Panama, Colombia and Ecuador.

Gustavia superba, for instance, is abundant in re-growing secondary forests and is distributed across northern South America, from southern Panama through the Andes to Ecuador, along the Caribbean coast, and in the Amazon basin (Mori & Kallunki, 1976). *Gustavia angustifolia*, on the other hand, is native to the dry deciduous forests of the coastal plain of Ecuador and Colombia (Prance & Mori, 1979).

In Panama, *C. foraseminis* has been found within seeds of *G. superba* collected in the forests of Barro Colorado Island. Adult moths emerged from most of the collected seeds approximately 6 weeks after fruit drop (Harms & Aiello, 1995). Interestingly, up to 14 individuals have been found in a single *G. superba* fruit, a striking difference to *C. foraseminis* found in cocoa, where a single individual is usually found per fruit (Harms & Aiello, 1995). Whether this difference is only related to the high availability of cocoa pods found in cocoa plantations in comparison to the potentially scarce and patchy presence of *Gustavia* fruits in the forest remains an open question. Another potential host for *C. foraseminis* is the Pequi tree (*Caryocar brasiliense*) in Brazil (de Oliveira & de Castro, 2017).

Researchers have noted the lack of knowledge about the seed-drilling Sesiidae of South America, which is an uncommon behaviour compared to other species of the genus that typically feed on trunks, branches, and roots (Harms & Aiello, 1995), as is the case for the closely related species *C. theobromae* that can be found on cocoa but it is particularly relevant as a guava trunk pest (Pulido Blanco et al., 2020). This calls for further research to better understand the ecology and behaviour of *Carmenta foraseminis* and its interactions with its host plants. For example, is *C. foraseminis* present on wild cocoa trees or other *Theobroma* species, or in other closely related genera such as *Herrania*?

Geographic distribution of *C. foraseminis*

Literature indicates that *C. foraseminis* is distributed in southern Central America and northern South America, with its incidence currently on the rise in the region (Figure 3). Records dating back to 1995 show the presence of *C. foraseminis* in Panama, Colombia and Venezuela (Eichlin, 1995; Harms & Aiello, 1995). Although still controversial, there are suspicions that the moth spread to Brazil in 2011 (Benassi et al., 2013). While the presence of this species is suspected in Ecuador, there is no official mention in the literature.

In Colombia, a study conducted in 2016 revealed that 77% of 65 cocoa farms across nine departments tested positive for the presence of *C. foraseminis* (Carabalí Muñoz et al., 2018). In Peru, the species likely emerged in cocoa plantations during the 2000s, with official registration in 2007 in Satipo (Alomía, 2015). A survey conducted in 2017 in the Huanuco region of Peru found *C. foraseminis* present in 93% of 165 visited farms across 63 communities (Cabezas et al., 2017).

The spread of *C. foraseminis* in the region is evident from the increasing number of studies produced in recent years. Until 2012, Venezuela was the sole country publishing on *C. foraseminis*. However, from 2013 to 2017, Colombia surpassed Venezuela in the number of publications on this pest, and since 2017, Peru has also begun contributing to the literature (Figure 1). While the distribution map constructed from available data (Figure 3) may not perfectly reflect the actual population density of *C. foraseminis* in the Amazon basin, it offers an overview of the regions where the pest is receiving attention. This attention is likely associated with the detrimental impacts of the pest on local cocoa sectors.

It is noteworthy that the four states receiving the most attention, chronologically, have been Aragua in Venezuela, followed by Antioquia in Colombia, and more recently San Martin and Huánuco in Peru (Briceño Vergara, 1986; Castaneda et al., 2015; Delgado et al., 2017). It is challenging to ascertain whether the focus on the pest in these states is due to its impact or if the presence of interested researchers and research centers has mediated this attention. However, it is apparent that the incidence of *C. foraseminis* has been increasing since 2000 in all countries within the Amazonian basin, posing an additional threat to cocoa production in the region (Figure 3).

This review underscores the necessity to update the geographical distribution of *C. foraseminis* in the region, monitor its expansion and implement proper management strategies. Establishing an initiative to determine the species' geographical distribution, perhaps through a participative platform for sharing information on its presence, would facilitate this.

Effects on cocoa production

Symptoms on cocoa fruit

Detecting the presence of *C. foraseminis* in cocoa fruit is challenging, particularly in the early stages of infection. Symptoms are not easily discernible until later stages of the infestation. In fact, identifying the eggs or larvae on the pod is difficult due to the nearly intact epicarp (Figure 2d). The most prominent and frequently observed symptoms attributed to *C. foraseminis* are the dark exit holes, approximately 0.5 cm in diameter (Figure 2e), which are excavated by the larvae during the prepupation phase. Additionally, exudates, such as excrement or suppuration, are often expelled through the exit orifice, providing further evidence of the pest's presence. These visible signs serve as key indicators for monitoring the incidence of *C. foraseminis* infestations in cocoa crops (Navarro & Cabaña, 2006).

At this stage, a substantial portion of the cocoa fruit's interior is typically compromised due to *C. foraseminis* infestation. Larvae directly damage cocoa by penetrating the mesocarp to reach the placenta of the fruit. They feed on the mucilage and seeds, resulting in perforated seeds and the presence of brown excretions within the fruit (Delgado et al., 2023). In addition to direct fruit damage, the presence of this pest can also disrupt cocoa pod development. *Carmenta foraseminis* lays its eggs before the fruit reaches full maturity, usually around 2 to 3 months prior to ripening (Luna Quispe, 2019; Sotomayor Parian & Soto Cordova, 2018). Notably, cocoa fruit becomes increasingly susceptible to *C. foraseminis* infestation from approximately 3.5 months onwards.

In Peru, instances of *C. foraseminis* infestation and resultant damage are higher during the peak cocoa fruit harvest season, which typically spans from April to July when the majority of fruits are produced (Cabezas et al., 2017). When the insect targets fruits that are less than 4 months old, premature ripening of the pods can occur (Cubillos, 2013). Timely detection of symptoms could prove instrumental in effectively managing this pest within cocoa plantations.

Incidence in cocoa plantations

The incidence of *C. foraseminis* attacks in cocoa plantations exhibited considerable variability, ranging from 0.02% to 70% of evaluated pods. This variability is influenced by factors such as the emergence time of the species in the region, as well as local environmental and phytosanitary conditions (Table 2). Studies suggest that higher temperatures, typically ranging between 23 and 27°C, tend to positively influence the incidence of *C. foraseminis* (Fachin et al., 2019; Muñoz Gutiérrez et al., 2017). Conversely, relative humidity levels, spanning from 71% to 96.6%, and plot elevation ranging between 496 and 745 m, do not appear to have a significant relationship with pest incidence (Fachin et al., 2019; Muñoz Gutiérrez et al., 2017).

The influence of rainfall on the incidence of *C. foraseminis* is not fully understood and appears to be more closely associated with cocoa phenology. In shaded sites within Colombia, adults of the species are prevalent during the rainy season, particularly on mature and near-ripe fruits, with their presence diminishing during periods of reduced rainfall (Carabalí Muñoz et al., 2018). Conversely, in Peru, the number of perforations per fruit caused by *Carmenta* spp. (including both *theobromae* and *foraseminis*) was observed to be higher during the dry season, exceeding 3.5 perforations per fruit, in comparison to approximately 2.5 perforations per fruit during the rainy season (Ccente Valenzuela, 2019).

Given that a typical infestation by *C. foraseminis* usually results in a single perforation, the observed phenomenon in the study may primarily involve *C. theobromae*. Notably, the highest incidence of damaged beans occurs during the rainy season (Ccente Valenzuela, 2019). Currently, there is limited information available regarding whether

TABLE 2 Variation in *C. foraseminis* incidence in the region.

Location	Incidence percentage	Comments	Source
State of Aragua, Venezuela	22.3% pods	During harvest period	Navarro and Cabaña (2006)
Huanuco, Peru	20% to 70% thus 34.6% pods	In 165 farms, 20 plants assessed per hectare	Cabezas et al. (2017)
Huanuco, Peru	38.7%	CCN-51 genotype	Moron Rojas (2018)
Huanuco, Peru	54.61%	CCN-51 genotype	Mezones Alarcon (2019)
Tingo María, Peru	45.18%	CCN-51 genotype	Jorge Panduro (2018)
Juanjui, Peru	54% pods		Fachin et al. (2019)
Tabalosos, Peru	30.2% pods		Fachin et al. (2019)
San Roque, Peru	25% pods		Fachin et al. (2019)
Satipo, Peru	70% of trees at least 1 and up to 4 pods infected	Random selection and evaluation of plants in a hectare	Alcantara Veliz (2013)
Antioquia, Colombia	55% pods		Carabali Muñoz et al. (2018)
Boyaca, Colombia	0.02% pods		Carabali Muñoz et al. (2018)
Antioquia, Colombia	58% pods	Between August 2013 and Mach 2014	Muñoz Gutiérrez et al. (2017)

adults of these species remain within cocoa plantations, or how factors such as distance to forests or the presence of natural hosts influence their presence or incidence. Additionally, there is a lack of understanding regarding the flight distance of these insects and the impact of adjacent land use on the survival of *Carmenta* spp. While such knowledge gaps persist, further research in these areas could provide valuable insights into population connectivity within specific regions and the colonization processes within plantations.

Co-infection between *Carmenta* and diseases

As anticipated, given the high disease pressure prevalent in the Amazon basin, instances of co-infection involving *C. foraseminis* and fungal and/or oomycete diseases have been documented. In Venezuelan cocoa farms, the most severely affected pods were found to be simultaneously infected by *C. foraseminis* and pathogens, predominantly *Phytophthora palmivora* (causing black pod rot) and *Monilia roreri* (causing frosty pod rot) (Parra et al., 2009). Similarly, in Peru, approximately 76% of the pods afflicted by *C. foraseminis* exhibited concurrent damage from black pod rot or frosty pod rot (Fachin et al., 2019).

It is probable that *C. foraseminis* contributes to the prevalence of these two diseases in cocoa (Mezones Alarcon, 2019), although the precise mechanism remains elusive. Whether *C. foraseminis* exhibits a preference for already infected pods or facilitates infection by breaching the pod skin facilitating pathogen entry requires further investigation. Tree-level simulations suggest that *C. foraseminis* shows a preference for healthy trees rather than those already infected (Arias et al., 2022), but the interaction at the cocoa pod level remains unexplored. On recently infected fruits, the co-occurence of *C. foraseminis* and *M. roreri* appears to be much less common than co-occurrence with *P. palmivora* (Ramos et al., 2024). Investigating whether this occurrence pattern is linked to different host stage preferences by the pests and/or to an existing mechanism of co-infection between *C. foraseminis* and pathogens such as *P. palmivora* (facilitation, exclusion) would be of interest.

Cocoa production losses due to *C. foraseminis*

Pests can cause direct harm to plants through their feeding behaviour on leaves or by burrowing into fruits, stems, and roots. One larva can affect three to four seeds per fruit, depending on the phenological stage of the fruit and the cocoa genotype (Moron Rojas, 2018).

They can also lead to indirect damage by creating openings that facilitate infection by bacteria, viruses, oomycetes or fungi. The exit hole left by adult *C. foraseminis* opens the way to significant secondary damage, including the entry of rainwater, opportunistic fungi and bacteria, and other insects, which can lead to higher seed loss (around 70% to 90%) compared to direct seed loss caused by larval feeding activity (Cabezas et al., 2017). In Peru, yield losses due to damage by *C. foraseminis* (direct or indirect) were estimated to be around 11% per harvested cocoa pod (Alcantara Veliz, 2013). In Colombia, within agroforestry systems, a total of 6325 pods were harvested over 8 months, of which 2673 (42%) were healthy and 3652 (58%) were damaged by *C. foraseminis*. The total production during this period was 366.5 kg of wet cocoa, while without damage from *C. foraseminis*, the potential harvest was estimated at 479 kg. The average yield of a healthy pod was 79.4 ± 11.2 g of wet cocoa, whereas, with pest damage, it was 46.9 ± 9.6 g of wet cocoa (equivalent to an average yield loss of 32.5 ± 9.1 g per infested pod). The average total loss was 23.5%, or 112.5 kg of wet cocoa, equivalent to 39.3 kg of dry commercial cocoa (Muñoz Gutiérrez et al., 2017).

Impacts of *C. foraseminis* on cocoa quality

These secondary infections promote the fermentation and decomposition of placental material (Carabalí Muñoz et al., 2018), which subsequently affects the fermentation of the beans post-harvest and can thereby reduce cocoa quality. Insect intrusion into pods can diminish the levels of sugars and proteins in the harvested cocoa, resulting in a loss of bean quality (Cubillos, 2013; Navarro & Liendo, 2007). Harvesting the fruit before the adult emerges, often before the fruit is ripe, may recover more than 90% of its beans. However, the collected beans may have inferior quality due to the presence of larvae inside the pods, and early harvesting before bean maturation can affect flavour (Cubillos, 2013; Navarro & Cabana, 2006; Navarro & Liendo, 2007). After infection by *C. foraseminis*, the beans may adhere and harden under the effect of pathogens, rendering them unusable in commercial form (Cubillos, 2013; Navarro & Liendo, 2007).

In Peru, it was estimated that infestation by *Carmenta* on a pod causes 50.4% damage to the seeds, with 9.5% of the seeds being completely lost (not exploitable on any market) (Ramos et al., 2024). These damages are very similar to those described for the CPBs in Asia. Unripe pods are difficult to depulp, contain less sugar and fat and have smaller nibs and compounds that contribute to the potential flavour. Additionally, fermenting pods with low pulp sugar content do not allow sufficient rise of temperature in the cocoa mass, resulting in slower and less vigorous fermentations, and do not produce the desired cocoa flavour (Schwan, 1998). Seed loss is a better indicator than the incidence of the real impact of *C. foraseminis* on cocoa cultivation and farmers' incomes. More studies should be developed in this regard.

Control

Over the past decade, several control strategies have been trialled, drawing from both farmer-derived insights and research on CPBs.

Monitoring

Regular monitoring is essential for estimating population abundance and distribution of pests, facilitating the implementation of appropriate response strategies (Carabalí Muñoz et al., 2018). By conducting periodic sampling and identification of signs of damage in both cocoa pods and alternative hosts, it becomes possible to mitigate population growth and dispersal. From our literature search and despite its acknowledged importance in controlling CPB (Meilin et al., 2023) we could not find a monitoring program for CPB in Indonesia. We did not find any niche modelling study that could help predicting the more suitable areas where CPB will stablish in the future. Probably the lack of forecasting studies including monitoring and modelling magnified the incidence of CPB in the region as cocoa farmers that were located in the CPB's expansion front were not well-prepared for it. Establishing a monitoring strategy for *Carmenta* expansion in the Amazon basin could greatly assist farmers in addressing the potential impact of this emerging pest. As highlighted by Cubillos (2013), uncontrolled movement of infested fruits between areas is one of the primary means of *C. foraseminis* spread. Therefore, restricting the transportation of infected pods from one region to another could serve as an effective control measure to contain its geographical expansion across cocoa-producing countries (End et al., 2021). Additionally, providing training to farmers and technicians to recognize symptoms caused by *C. foraseminis* could contribute significantly to slowing down the pest's progression. Some monitoring programs on pests and diseases are established in the Amazon and are managed by local stakeholders (government, cooperatives and universities, Aguilar and Cabezas personal communication). Hopefully, the region will take profit of their beneficial effect at mitigating *C. foraseminis* incidence and expansion.

Cultural control

Cultural control methods are crucial for creating conditions that discourage pest development and minimize crop susceptibility. Drawing on successful strategies implemented for managing CPB in Asia, specific practices have been adapted to control *C. foraseminis*, including pruning, timely harvesting, treatment of infected cocoa pod husks and effective weed management (Carabalí Muñoz et al., 2018; Cubillos, 2013). These approaches have demonstrated the potential to reduce CPB in Indonesia (Mulyani & Bakti, 2021). Similarly, they can reduce *C. foraseminis* incidence by up to sevenfold, depending on the level of management and prevailing environmental conditions (Jorge Panduro, 2018; Piundo Aguilar, 2019; Tobar Aguilar, 2022).

Pruning serves to enhance plant illumination and airflow, deterring pest presence and maintaining an ideal plant height of less than 3 m, facilitating the detection and treatment of fruits damaged by *C. foraseminis* and other diseases. Timely harvesting at intervals of every 14 days significantly decreases the proportion of fruits exhibiting indirect damage.

Reducing the harvesting interval to 10 or 12 days during peak harvest periods could be beneficial. Studies have shown that with shorter intervals, 90% of fruits affected by *C. foraseminis* exhibit only light direct damage, and from these fruits, 95% of the beans can be recovered (Cabezas et al., 2017). This phytosanitation practice aligns with recommendations for disease control, including frosty pod rot and witches' broom (Ten Hoopen & Krauss, 2016). However, the economic costs, associated with labor, need to be carefully evaluated against the actual benefits.

In contrast, harvesting every 21 days is strongly discouraged. With longer intervals, *C. foraseminis* adults can emerge, allowing fungi to enter the pod, potentially increasing the percentage of indirect damage to up to 80% of beans inside infested pods (Cabezas et al., 2017).

Disfavoring the practice of extracting cocoa beans *in situ* after harvesting is advisable. This method can create new infection sites as pupae might remain intact on the pod, facilitating access to unharvested fruits by adults upon emergence (Carabalí Muñoz et al., 2018). Similar to disease control measures, covering cocoa pod husks with plastic is recommended to prevent adult emergence and reproduction. Additionally, applying effective microorganisms can accelerate organic matter decomposition and reduce pest and disease inoculum.

The efficiency of managing this pest depends on growers' decisions to invest in higher labour input systems of production. Failures in pest and disease management, as observed with the CPBs in Asia, may result from low investment in cultural practices due to factors such as low income per capita stemming from the low quality of cocoa beans affected by CPB (Saleh & Ahmad, 2020).

Genetic selection of resistant host plant

Genetic control is recognized as one of the most effective approaches to manage diseases and pests in agricultural crops, including cocoa (Nyassé et al., 2007; Phillips-Mora et al., 2005; Teh et al., 2006). Certain cocoa genotypes exhibit better tolerance to pest infestation, thereby mitigating the impact of pests on the crop. Additionally, some genotypes may possess inherent resistance to infestation of agents such as the CPB, often attributed to factors such as higher pod hardness (Teh et al., 2006). Through selective breeding and genetic improvement programs, these desirable traits can be further enhanced, contributing to more resistant/tolerant and productive cocoa varieties.

The impact of the genetic origin of cocoa on the susceptibility to *C. foraseminis* remains a topic of debate. While Cubillos (2013) suggested that certain cocoa clones such as ICS-1, ICS-39, ICS-60, ICS-95, TSH-565 and SCC-61 are highly susceptible to *C. foraseminis*, others like IMC-67, PA-46, PA-150 and CCN-51 exhibit a higher degree of tolerance. However, field observations, particularly in Peru, challenge the supposed tolerance of CCN-51 to the insect (Alomía et al., 2021). Additionally, research by Delgado et al. (2017) indicated that the clone ICS-1 had a significantly lower infestation rate compared to other clones evaluated. Furthermore, a study by Tobar Aguilar (2022) found no significant difference in tolerance to *C. foraseminis* between hybrid and grafted plants in Colombia. The complex interaction between host susceptibility, environmental factors and the pest's behaviour in selecting hosts, especially concerning genetic and phenological traits, warrants further investigation.

Mechanical control

Enclosing fruits infected by *C. foraseminis* in plastic bags for 3 months can effectively eliminate eggs, larvae and adults, thereby disrupting the pest's life cycle. This method leverages sunlight exposure within the plastic bags, leading to asphyxiation of the pests, a technique demonstrated to be effective for controlling pests like the CPB (Rosmana et al., 2010; Saripah et al., 2005, 2007). Similarly, covering pods on trees with bags creates a physical barrier that prevents pest entry and exit (Luna Quispe, 2019). Pod-sleeving, whether using degradable or regular plastic, has shown promise for controlling CPB, particularly in small-scale cocoa plantations, by preventing insect dispersal and protecting pods from opportunistic fungal infestation (Saripah et al., 2005; Sembel et al., 2011). However, pod-sleeving is labour-intensive and thus costly, similar to phytosanitation practices. It can also increase the risk of losses due to physiological pod death and black pod rot and raises concerns about plastic waste recycling (Bagny-Beilhe et al., 2018).

Chemical control

The use of synthetic insecticides to control CPB remains widespread among Indonesian farmers, although they keep reporting high losses despite spraying it (Ruf, 2007). Application of deltamethrin 25 ppm, a contact pesticide, on four-month-old pods and on the lower branches of cocoa trees every 2 weeks has been shown to significantly reduce losses related to *C. foraseminis* 40 days after the first insecticide application (Cubillos, 2015). The insecticide demonstrated a lethal effect on adult insects, potentially affecting eggs as well, thereby reducing their populations and subsequent crop damage and losses. Although fipronil might be more effective at controlling CPB (highest percentage of good wet cocoa beans in the study, Saripah & Alias, 2016), deltamethrin has also been proven effective against this pest (17.8% yield loss to CPB in comparison to 62.78% for the control treatment, Rimbing et al., 2019). Considering the lifecycle of the pest, which is mostly contained within the pod, chemical control appears to be ineffective unless applied during the adult emergence phase. Targeting deltamethrin applications to coincide with peak adult populations of *C. foraseminis* is crucial for effectiveness. However, considering the adverse effects of chemical inputs on human and ecosystem health, it is prudent to explore and develop alternative solutions and to more effectively determine if and which types of chemical pesticides could be used under specific conditions.

Semiochemical control

Semiochemical control involves the use of informative natural compounds (pheromones or allelochemicals) that act to repel phytophagous insects, reduce reproductive potential or attract natural enemies. The use of synthetic sexual pheromones associated with traps can increase adult mortality (by trapping) and prevent male insects from finding females and mating (mating disruption), thereby reducing female fecundity and overall pest dynamics (Djoukwe Tapi et al., 2018). Several trials of homemade traps with different attractants (human fermented urine, sugar cane treacle, cocoa pulp juice, an alimentary attractant: GF-120™) were conducted in Peru to capture *C. foraseminis* adults (Cabezas et al., 2017; Peralta Murga, 2022). These traps were mostly ineffective, with only human-fermented urine proving effective at attracting individuals, and even then, only between one and 14 individuals were trapped using this attractant. In

Colombia, a McPhail trap containing hydrolyzed and boronized proteins of corn at 10% captured an average of four adults per week, demonstrating its potential effectiveness for pest monitoring and eventual control (Montes Prado et al., 2017). Pheromones of CPB have been well described (Beevor et al., 1986; Beevor, Day, & Mumford, 1986), confirmed to be effective at attracting males (Beevor et al., 1993; Beevor, Day, & Mumford, 1986), and proved to be similar to more effective than spraying chemical pesticides at reducing cocoa pods infected by CPB (Vanhove et al., 2020). This shows the enormous potential of using pheromones at controlling Lepidoptera cocoa pests. However, there are currently no specific pheromones of *C. foraseminis* that have been identified or successfully extracted or manufactured, to be used as control this pest on traps based on sexual confusion.

Biological control

Biological control is defined here as the use of living organisms (such as entomopathogenic bacteria, fungi, nematodes, parasitoids and predators) to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be (Eilenberg et al., 2001).

Predators and parasitoids

Generalist and specific predators play a crucial role in controlling pests by killing and feeding on multiple individual prey during their lifetimes, making them valuable tools in pest management (Symondson et al., 2002). In Colombia and Peru, several parasitoids have been identified parasitizing different developmental stages of *Carmenta* spp. feeding on cocoa or guava in the field. These include egg parasitoids such as *Trichogramma* sp. (Hymenoptera: Trichogrammatidae), *Gryon* sp., *Telenominus* sp. and *Telenomus* sp. (Hymenoptera: Scelionidae); several larval-pupal parasitoids including *Brachymeria* sp. (Hymenoptera: Chalcididae), *Pimpla sanguinipes*, *Scolomus* sp. (Hymenoptera: Ichneumonidae), *Bassus brullei*, *Bracon* sp., *Parapanteles* sp. and *Apanteles* sp. (Hymenoptera: Braconidae); and pupal parasitoids such as *Calliephialtes* sp. (Hymenoptera: Ichneumonidae), *Brachymeria pedalis* and *B. conica* (Hymenoptera: Chalcididae) (Muñoz Gutiérrez et al., 2017; Piundo Aguilar, 2019; Pulido Blanco et al., 2020). Some genera were found parasitizing both larvae and pupae of *Carmenta theobromae* feeding on guava. These genera include *Baryscapus* (Hymenoptera: Tetrastichinae), *Eurytoma* (Hymenoptera: Eurytomidae), *Toechorychus*, *Lissonota* (Hymenoptera: Ichneumonidae), *Polstonia* (Hymenoptera: Pteromalidae), *Siphostumia* and *Sturmiomima* (Diptera: Tachinidae) (Pulido Blanco et al., 2020). See Table 3 that only includes genera and species found on *C. foraseminis* associated to cocoa pods.

Some preliminary experiments have shown promising results regarding the efficacy of predators in controlling *Carmenta* populations. In Venezuela, for instance, emerging *Trichogramma pretiosum* larvae were capable of consuming *Carmenta* eggs within 4 to 5 days (Navarro & Cabana, 2006). However, to achieve effectiveness in the field, it is recommended to introduce between 100,000 and 500,000 adults per hectare, depending on the infestation rate and also on the financial capacity of the producer (Navarro & Cabana, 2006). The eggs of parasitoids should be released on the branches of cocoa trees every 50 m, at the height of the pods, due to the dispersal capacity of adult *T. pretiosum* (around 19 m).

According to Cubillos (2013), regular release of *Trichogramma exiguum*, *T. atopovirilia* and *Chrysoperla carnea* is required to have significant negative effects on *Carmenta* populations. Many larval predators like *Polistes* sp. and *Polybia* sp. (Hymenoptera: Vespidae) have also been identified so far (Muñoz Gutiérrez et al., 2017; Piundo Aguilar, 2019) (Table 3). However, no work has been reported on the effect of ants, which are known to be generalist predators of pests in many tropical systems (Philpott & Armbrecht, 2006). Indeed, negative impacts of cocoa black ants (*Dolichoderus thoracicus*), weaver ants (*Oecophylla smaragdina*), crazy ants (*Anoplolepis* spp.) and Saint Valentine ants (*Crematogaster* spp.) have been documented on CPB in Asia (Gassa et al., 2015; Gassa et al., 2016). Thus, farmers in Asia favour the establishment of native black ant colonies in cocoa plantations to reduce damage caused by CPB (Gassa et al., 2015; Gassa et al., 2016). Bats and birds are also generalist predators known to enhance cocoa yields through herbivory reduction (Ferreira et al., 2023; Maas et al., 2013; Vansynghel et al., 2022), but no specific work has been conducted to test their effect on *Carmenta*. It would be relevant to investigate further the effect of these predators on *C. foraseminis* incidence and the factors that could influence their presence (e.g. shade tree cover, nesting boxes, herbaceous vegetation and native flora) to develop conservation biological control strategies.

Entomopathogens

Entomopathogens are microorganisms, including certain bacteria, fungi, nematodes, protozoa and viruses, that can infect and kill the host. Only a few studies have looked at the effects that entomopathogens might have on *C. foraseminis*. For instance, the entomopathogenic nematode *Steinernema* spp. (trade name NEMA G, concentration of 10,000 juvenile infectious units per *C. foraseminis* larva) applied directly to the pod caused 100% lethality of the late stages of *C. foraseminis* larvae (Cubillos, 2014) under laboratory conditions in Antioquia, Colombia. In Indonesia, a combination of pod sleeving and nematode application had a synergistic reduction of pod damage by CPB, resulting in totally healthy pods (Rosmana et al., 2010).

The pathogenicity of indigenous strains of *Beauveria bassiana* (from the regions of Tabalosos and Juanjui, Peru) was confirmed on the egg stage of *C. foraseminis* under laboratory conditions at a concentration of 8×10^6 conidia mL^{-1} (Davila Tafur, 2018). In Colombia, laboratory experiments were conducted to test the pathogenicity of two indigenous strains of *Paecilomyces* sp. and *Lecanicillium* sp. on larvae of *C. foraseminis* (Medina et al., 2013). The larvae were immersed in suspensions of the isolates containing different concentrations of conidia, ranging from 0 to 10^8 mL^{-1}. For both strains, larval mortality was directly proportional to inoculum concentrations, with *Lecanicillium* sp. showing greater effectiveness against larvae.

TABLE 3 Natural enemies of *C. foraseminis* according to the pest development stage they attack. All *C. foraseminis* individuals that were parasitized/predated were found on cocoa pods.

Natural enemy	Development stage of *C. foraseminis*	Efficacy	Source
Brachymeria sp. Westwood.	Larva & Pupa		García and Montilla (2010); Carabalí Muñoz et al. (2018); Medina and Moscoso (2018); Muñoz et al. (2017); Piundo Aguilar (2019)
Calliephialthes sp. (Ichneumonidae)	Pupa		García and Montilla (2010); Piundo Aguilar (2019)
Carpophilus sp.	Larva		Piundo Aguilar (2019)
Labidura sp.	Larva		Piundo Aguilar (2019)
Polybia sp.	Larva		Piundo Aguilar (2019)
Polistes sp. (Hymenoptera: vespidae)	Larva		Carabalí Muñoz et al. (2018); Muñoz et al. (2017)
Promicrogaster sp. Brues et Richardson (Braconidae)	Pupa		García and Montilla (2010)
Steinernema spp.	Larva & Pupa	10000Ji/ larva = 100% lethality	Cubillos (2014)
Telenominae sp.	Egg		Carabalí Muñoz et al. (2018)
Telenomus sp. (Hymenoptera: Scelionidae)	Egg		Muñoz et al. (2017); Cubillos (2013)
Trichogramma pretiosum Riley	Egg		Navarro and Cabaña (2006); Carabalí Muñoz et al. (2018); Muñoz et al. (2017)
	Pupa		García and Montilla (2010)

Under field conditions in Peru, the efficacy of different products on the incidence of *C. foraseminis* (and other pod diseases) was tested. These products included the following: (1) a mixture of entomopathogenic fungi *B. bassiana*, *Lecanicillium lecanii*, and *Metarhizium anisopliae* (commercial name Arrazador®); (2) a suspension of the bacterium *Bacillus thuringiensis* (commercial name Best-k®); (3) a mixture of the previous suspensions; (4) a chemical insecticide composed of Lufenuron + Emamectin Benzoate (Kieto®); and (5) a water-based control (Jorge Panduro, 2018). The five treatments were applied directly to CCN-51 pods and on the soil using handheld sprayers. This was done following a randomized complete block design consisting of three blocks, with nine plants per replicate. The effectiveness of each treatment was evaluated every 15 days during a single cocoa production season, which included flowering and fruiting. After 4 months, the mean incidence of *C. foraseminis* was three to four times higher on control trees compared with the other treatments.

The use of the three entomopathogenic fungi alone or in combination with bacteria (*Bacillus thuringiensis*) was found to be the most effective treatment against *C. foraseminis*, even more so than the chemical insecticide Kieto® (Jorge Panduro, 2018). However, *B. thuringiensis* alone was not very effective against *C. foraseminis* (Cubillos, 2014). Several Cry1-class proteins of *B. thuringiensis* have also been shown efficient in killing CPB larvae in lab bioassays but their efficiency in cocoa plantations has not been tested yet (Santoso et al., 2004). Both entomopathogenic nematodes (*Steinernema* spp.) and fungi show promise in controlling different stages of *C. foraseminis*, but their actual contribution to pest control needs to be verified under field conditions. Further investigations are necessary to assess the control mechanisms, optimal doses, application frequency and application process of these biocontrol agents.

Use of botanicals and minerals

Zingiberaceae essential oils effectively reduce the emergence of healthy CPB adults in comparison to the control treatment (Saripah et al., 2020). Similarly, research on plant extracts as a means of controlling *C. foraseminis* has shown promising results. Extracts from *Simarouba amara* and *Lonchocarpus utilis* were found to have control effects on *C. foraseminis*, with *S. amara* extract demonstrating greater efficacy when applied to cocoa pods (Pinedo Aguilar, 2021). Mineral broths have also been investigated for their impact on *C. foraseminis*. Bordeaux mixture and sulfocalcic broth, commonly used to control cocoa diseases, have shown effects on the incidence of *C. foraseminis*. Following monthly applications of 2% Bordeaux broth and 10% sulfocalcic broth on 2.5-month-old fruits for 1 year, the incidence of *C. foraseminis* decreased by 17% to 45% compared to the control (Cabezas et al., 2017; Moron Rojas, 2018) in the Huanuco province of Peru. These applications may have prevented oviposition by acting as a repellent or providing mechanical protection against external aggression, but further research is needed to understand the mechanisms behind these results.

DISCUSSION

Our review strongly suggests the expansion of *C. foraseminis* in cocoa cultures in the Amazonian region in terms of its presence and distribution. On average, infestation rates between 20% and 40% have been reported in plantations, a significant figure in the same order of magnitude as incidences of the traditionally considered the most damaging pathogen agents in the region: *Moniliophthora roreri* and *Phytophthora palmivora*. In this context, the losses associated with the presence of *Carmenta* undoubtedly pose a significant risk to cocoa production in the Amazonian region. However, whether its incidence in cocoa plantations and its impact on production are indeed increasing and whether it will reach the level of threat posed by Cocoa Pod Borer (CPB) in Asia remain uncertain and only time and the measures implemented at present will provide the answer.

Around one-third of the information related to *Carmenta* that was used in this study constituted grey literature such as theses and dissertations from national universities, and served as a reliable gauge of the topics capturing attention within a country. It reflects current interests and can hint at future priorities (Mahood et al., 2014). So far, the increasing volume of grey literature produced by local universities and research centres in northern South America, suggests the growing importance of *C. foraseminis*. One possible explanation is its recent emergence, as it typically takes time for an emerging pest to garner sufficient attention and data for publication in international journals. Additionally, since its spread is currently confined mainly to the Amazonian basin, there might be less incentive for researchers to publish in international journals. Financial constraints within certain national universities in Latin America could also hinder publication in international outlets. Given the urgency of addressing this pest and finding solutions for producers, it is advisable that national research organizations prioritize swiftly disseminating their findings—even if not peer-reviewed—over the longer process of publication in peer-reviewed journals.

As previously mentioned, the emergence of *C. foraseminis* poses numerous questions regarding its ecology, its demography, its potential socio-economic impact on cocoa cultivation, the process of its emergence and the most suitable strategies to control it. In terms of interactions of *C. foraseminis* to other diseases locally present, it is important to explore whether *C. foraseminis* is replacing one or more of the main cocoa diseases and, if so, how this replacement occurs through the cocoa production season along the different regions. Another interaction that is worth studying is whether *C. foraseminis* facilitates infection and/or colonization of cocoa pods by any of the predominant cocoa diseases in the area, and by which mechanisms. Understanding these interactions is essential to estimating primary and secondary losses produced by *C. foraseminis* and its contribution to the total losses for farmers. Hence, further research and monitoring efforts are needed to elucidate the dynamics of these interactions and develop effective strategies for managing *C. foraseminis* in cocoa production systems.

Regarding the demography of the species, the swift population growth and geographical distribution of *C. foraseminis* suggest at least two plausible scenarios: either a recent and unique cocoa colonization event (host-switch) followed by invasion of interconnected cocoa farms, or multiple local spillover events where *C. foraseminis* adopted cocoa (and/or related species within *Theobroma* and *Herrania* genera) as host plants. The first hypothesis has been documented in other invasive pests (Hufbauer et al., 2012). Investigating the recent demographic history of *C. foraseminis* and the common or dissimilar origins of the multiple populations is feasible using genetic methodologies and is crucial for informing the development of effective management policies to curb its expansion.

Our review suggests that *C. foraseminis* has expanded in the Amazon region and that it can keep expanding if it finds suitable conditions. However, we reported that infestation rates of *C. foraseminis* exhibit significant differences among cocoa plantations and countries. Understanding such heterogeneity is essential to mitigate *C. foraseminis* incidence and expansion. Despite the considerable research conducted on these aspects, it remains largely unclear whether such infestation differences can be attributed to variations and interplay of factors such as the pest and disease control methods employed by farmers, the historical context of the territory, the biotic conditions of the plot including the presence of other potential host plants, the abundance of natural enemies, differences in the cocoa microbiome or the presence of other *Carmenta* species, abiotic factors such as temperature, elevation, and humidity. Even less is known about the evolutionary interplay between these environmental factors and *C. foraseminis* potentially leading to local genetic adaptations of this pest species. Studies that integrate ecology, social sciences and genetics hence hold the potential to elucidate the relative importance of these elements in driving variations in *C. foraseminis* infestation rates. By identifying factors that can be modified to effectively reduce the impact of *C. foraseminis*, such interdisciplinary research efforts can inform targeted interventions aimed at mitigating pest infestations. Additionally, these studies can facilitate the development of risk maps, enabling the identification of regions where efforts should be particularly intensified to combat *C. foraseminis* effectively. Implementing sustainable practices that enable farmers to combat *C. foraseminis* and the entire consortium of locally important pests and diseases is necessary. *Carmenta foraseminis* likely contributes to increased losses in already poorly performing systems, making it even more challenging for farmers to attain a living income from cocoa production. Addressing these challenges requires collaborative efforts among researchers, farmers and policymakers to develop effective and sustainable strategies for pest management in cocoa production systems.

AUTHOR CONTRIBUTIONS

Mónica Arias: Investigation; writing – original draft; writing – review and editing. **Philippe Ninnin:** Data curation; investigation; writing – original draft; writing – review and editing. **Martijn Ten Hoopen:** Conceptualization; resources; writing – review and editing. **Jhoner Alvarado:** Investigation. **Oscar Cabezas Huayllas:** Investigation. **Bruno Valderrama:** Investigation. **Gabriel Alguilar:** Investigation. **Charles Perrier:** Writing – original draft; writing – review and editing. **Frédéric Dedieu:** Investigation. **Leïla Bagny Beilhe:** Conceptualization; formal analysis; funding acquisition; project administration; supervision; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All sources used on this review are cited in the reference list.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Appendix S1. Spanish translation.

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