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Chrysodeixis chalcites, a pest of banana crops on the Canary Islands: Incidence, economic losses and current control measures

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ABSTRACT

Chrysodeixis chalcites is an emergent pest in bananas (*Musa acuminata* Colla) grown on the Canary Islands. Feeding damage to leaves and fruit and the control measures targeted at this pest were evaluated over a two-year period (2013–2014). The prevalence of infestations (42–100%) on the islands was similar during the two years of the study. Mean foliar damage (1.5–7.3% depending on island) and fruit damage (1.0–5.7%) detected in field surveys varied significantly across islands, plantation aspect (north- or south-facing) and season. Fruit damage was not correlated with foliar damage ($P > 0.05$). The weight of *C. chalcites* damaged bananas varied significantly (0.2–4.2% of harvested fruit) across islands, particularly in the spring. Overall, 3155 tonnes of bananas/yr are likely discarded due to *C. chalcites* damage, representing 1.5% of annual production or 2.68 million €/yr. The most frequently used pesticide was indoxacarb, usually applied on three occasions per crop cycle, for which the cost of control measures would average 240 €/ha per crop cycle. The direct damage that *C. chalcites* causes to banana fruit results in significant economic losses in addition to the direct costs of pesticide based control measures. Effective and sustainable control strategies are required against this pest.

1. Introduction

Banana (*Musa acuminata* Colla) represents one of the most important agricultural goods with an annual trade valued at nine billion dollars worldwide (Arias et al., 2003; Hallam, 1995; Raynolds, 2003). Banana is the main crop of the Canary Islands, representing 30% of total agricultural production (González-Concepción et al., 2008; Robinson and Galán-Saúco, 2010). In 2015, this crop was grown over an area of 8975 ha (i.e., 23% of the total cultivated area of the archipelago), with a total production of 381,983 tonnes, representing 0.3% of the world's banana production. The island of Tenerife is the largest producer of bananas in the Canary Islands (43% of the total production), followed by La Palma (33%) and Gran Canaria (22%), while the remaining 2% of production occurs on the islands of La Gomera, El Hierro and Lanzarote. Most of the production is destined to markets in the Iberian Peninsula (91%), and only a small fraction is exported to Western Europe (0.1%), whereas the remainder (8.9%) is consumed locally (ASPROCAN, 2016; MAPAMA, 2016). Banana production is also of great social importance in the Canary Islands as it employs over 7000 people, representing up to 10% of jobs on some of the islands. Many other sectors also provide services to, or depend on, banana production, including the tourism sector as banana plantations have become a destination for tourist visits (Bianchi, 2004; González-Concepción et al., 2008). Bananas are cultivated in mesh-built greenhouses on the warmer southern slopes and in the open-field on the cooler, northern areas of these islands. As such, crops grown under mesh tend to be more prone to phytosanitary problems (Del Pino et al., 2011; Galán-Saúco, 1992; Robinson and Galán-Saúco, 2010).

Banana crops present numerous phytosanitary problems, with the most important and widespread pest being the banana weevil *Cosmopolites sordidus* (Germar) (Carval et al., 2016; Gold et al., 2001). Lepidopteran pests species, on the other hand, have a local distribution; for example, the species *Antichloris viridis* Druce, 1884 and *Caligo memnon* C. Felder & R. Felder, 1867 are present in Venezuela, Costa Rica and other countries of Latin America (Liscano and Dominguez-Gil, 2005; Smilanich and Dyer, 2012); *Spodoptera litura* Fabricius, 1775 and *Chrysodeixis acuta* Walker, 1858 are present in India (Tayade et al., 2014) and *Chrysodeixis chalcites* (Esper) is an important pest on banana

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crops only in the Canary Islands. *C. chalcites* also affects numerous fruit, horticultural, ornamental and forest crops such as cotton, alfalfa, cabbage, sunflower, geraniums, beans, corn, turnips, potatoes, cucumbers, peppers, bananas, soybeans, tobacco and tomato (Cabello et al., 1996; Passoa, 1995).

Chrysodeixis chalcites was previously a minor pest on the Canary Islands banana crops that caused leaf damage which did not usually justify control measures (Del Pino et al., 2011). However, since 2000, this insect has shown marked changes in its feeding behavior for unknown reasons. Specifically, larvae have begun to feed on the skin of the banana fruit causing marked aesthetic damage that completely eliminates the commercial value of the fruit (Del Pino et al., 2011; Perera and Molina, 2007). As a result of this unusual behavior, *C. chalcites* is now the lepidopteran pest that requires the greatest number of insecticide treatments and control costs appear to be increasing over time (Del Pino et al., 2011; Domínguez et al., 2012).

Although *C. chalcites* larvae are known to seriously affect the saleable yield of banana (Del Pino et al., 2011; Perera and Molina, 2007), accurate estimates of pest-induced losses are not available. Determining the production losses and economic impact caused by this pest in banana crops in the Canary Islands is necessary for pest control decision-making. Pest population assessment is one of the fundamental aspects used to determine the need to use pest control interventions in Integrated Pest Management (IPM) programs. Since 2014, an IPM approach is mandatory in all crop production systems in Spain (Royal Decree 1311/2012, which incorporates European Directive, 2009/128/EEC that established a framework for the sustainable use of pesticides in the European Union). Effective decision-making in IPM also relies on understanding the relationships between pest numbers, plant responses to injury and the resultant economic losses (Higley and Pedigo, 1993; Pedigo, 1996).

The objective of the present study was to evaluate the incidence and feeding damage inflicted by *C. chalcites* as well as to estimate the production losses and economic impact of this pest on banana crops in the Canary Islands. We also aimed to estimate losses arising from direct damage to fruit and indirect costs involved in the purchase and application of insecticides targeted at this insect. The results of the present study are part of a wider approach to define *C. chalcites* damage thresholds in banana crops and the potential use of novel biological insecticides that are currently under development (Bernal et al., 2013; Simón et al., 2015).

2. Materials and methods

2.1. Evaluation of *C. chalcites* incidence and feeding damage

To evaluate the incidence and damage due to *C. chalcites*, surveys were conducted in commercial banana plantations both in open-field and mesh-built greenhouses, on the five main banana-producing islands of the archipelago: Tenerife, La Palma, Gran Canaria, La Gomera and El Hierro.

A total of 81 surveys were conducted over a period of two years, during the spring, summer and autumn of 2013 and 2014 (Table 1; Fig. 1S). Surveys were not performed during the winter (November–February), as previous studies demonstrated that the pest was absent or present in very low densities in the winter (Del Pino et al., 2011; Perera and Molina, 2007). Damage assessments were performed on thirty randomly selected plants following a zigzag pattern within each plantation. For this, each location was classified as infested or not by *C. chalcites* based on direct observation of feeding damage on leaves and fruit. *C. chalcites* was identified by the characteristic foliar perforations made by feeding of the larvae. Additionally, the captured larvae and adults were identified as *C. chalcites* following the procedures described in Gómez De Aizpurúa (1985) and Cabello and Belda (1994). The aspect of each banana plot (north- or south-facing) was also noted. Taking into account the number of banana plots with damage and the total number of plots analyzed, the prevalence of *C. chalcites* infestation for each island and aspect was calculated.

Foliar damage was evaluated in young banana plants (immature plants of less than 1 m height) (Fig. 2SA), using a visual scale with five categories: Category 0: no damage, Category 1: 5–20% leaf damage (percentage of leaf area showing damage), Category 2: 21–40% leaf damage, Category 3: 41–60% leaf damage and Category 4: > 60% leaf damage (Del Pino M, unpublished data) (Fig. 2SB). Damage to fruit, in contrast, was evaluated in adult plants (Fig. 2SA) by determining the percentage of damaged banana handles based on the total handles present on each bunch. A small fruit perforation characteristic of *C. chalcites* feeding in any finger (fruit) of the handle was considered as the entire handle affected (as the handle would be discarded during processing and packing); the area encompassing these damaged handles was then estimated based on the total number of handles and assigned to one of the following categories: Category 0: no damage, Category 1: 2–10% of the handles of the bunch damaged, Category 2: 11–25% of the handles, Category 3: 26–50% of the handles, Category 4: 51–75% of the handles, and Category 5: 76–100% of the handles (Fig. 2SC). Thereafter, average percentage severity of foliar and fruit damage was calculated using the formula described by Townsend and Heuberger (1943):

$$\left(\frac{\sum (\mathrm{nxv})}{\mathrm{VxN}}\mathrm{x}100\right)$$

where *n* is the number of sample units in each category, *v* the value of each category (0, 1, 2, 3, 4 or 5), *V* the value of the highest category and *N* the total number of sample units.

The data obtained on the island of La Gomera were not included in the analyses, as few surveys were performed due to the low incidence observed by the field technicians, and because just one survey was performed in 2013, where *C. chalcites* infestations were not found.

2.2. Estimation of economic losses caused by *C. chalcites*

Direct economic losses were estimated by sampling in banana processing facilities. A processing facility was selected on each island that received bananas from different areas (Fig. 3S). The processing facilities were located at San Miguel de Abona (Tenerife, 28° 6′ 11″ N, 16° 36′ 42″ W), Los Llanos de Aridane (La Palma, 28° 39′ 56″ N, 17° 54′ 32″ W), Gáldar (Gran Canaria, 28° 9′ 29″ N, 15° 39′ 37″ W) and Frontera (El Hierro, 27° 46′ 26″ N, 18° 0′ 40″ W). The packaging plant on Tenerife received bananas from 9 banana-growing zones across 5 municipalities. On La Palma, the packaging plant received bananas from 7 zones (3 municipalities). The packaging plant on Gran Canaria received bananas from 5 municipalities and the plant on El Hierro received fruit from one municipality (Fig. 3S). Each zone was sampled on at least three occasions.

A total of 30 surveys, from November 2014 to September 2015, were performed in the different banana packaging plants: 13 in Tenerife (samples taken from 26 different batches of fruit arriving from local municipalities mentioned above), 10 in La Palma (27 samples), 4 in Gran Canaria (20 samples) and 3 in El Hierro (20 samples). Each survey lasted 6 h during the morning processing and packaging activity in the plant (8.00–14.00 h).

Economic losses were estimated by weighing the fruit discarded due to *C. chalcites* damage. The total weight of discarded fruit was then obtained in relation to the total weight of fruit processed during the 6 h sampling period in each processing plant.

To extrapolate the losses across each island and their economic impact, the number of hectares cultivated in each island was considered, as well as the market price for bananas in 2015, which depends on their quality (ASPROCAN, 2016). The average annual banana production was 174,792 tonnes on Tenerife, 131,585 tonnes on La Palma, 78,935 tonnes on Gran Canaria, and 2856 tonnes on El Hierro. The

Table 1
Sampled localities with coordinates, north (N) or south (S) facing plots, crop system (OF: open-field and GH: mesh greenhouses) and number of plots inspected in each location with number of surveys conducted in each plot (in brackets) during spring (March to May), summer (June to August) and autumn (September to November) in 2013 and 2014.

Locality	Coordinates		North (N) or south (S) facing plots	Crop System OF/GH	Plots (Surveys)					
					2013			2014		
	Latitude (N)	Longitude (W)			Spring	Summer	Autumn	Spring	Summer	Autumn
Tenerife										
Arona	28° 01′ 47″	16° 39′ 07″	S	GH	–	3 (3)	2 (2)	5 (5)	2 (2)	–
Adeje	28° 04′ 19″	16° 43′ 02″	S	GH	–	1 (1)	–	1 (1)	–	–
Guía Isora	28° 13′ 08″	16° 49′ 40″	S	OF	–	–	1 (1)	–	–	–
Fasnia	28° 13′ 45″	16° 24′ 57″	S	GH	–	–	–	1 (1)	–	–
Güimar	28° 17′ 59″	16° 22′ 31″	S	GH	–	–	–	1 (1)	–	1 (1)
Los Silos	28° 22′ 30″	16° 48′ 01″	N	OF	–	–	–	–	–	1 (1)
Buenavista	28° 23′ 12″	16° 50′ 15″	N	GH	–	–	–	1 (1)	–	–
Puerto Cruz	28° 24′ 24″	16° 33′ 30″	N	OF	–	–	2 (2)	–	–	–
Valle Guerra	28° 31′ 04″	16° 24′ 25″	N	1OF/2 GH	–	1 (1)	1 (1)	–	1 (1)	–
Tejina	28° 32′ 24″	16° 22′ 44″	N	GH	–	–	–	–	1 (1)	–
La Palma										
Fuencaliente	28° 29′ 38″	17° 52′ 07″	S	OF	1 (1)	2 (2)	–	–	–	2 (2)
El Remo	28° 33′ 18″	17° 53′ 15″	S	GH	–	–	–	–	1 (1)	1 (1)
Charco Verde	28° 34′ 26″	17° 53′ 55″	S	1OF/1 GH	1 (1)	1 (1)	–	–	–	–
Mazo	28° 35′ 43″	17° 45′ 33″	N	OF	–	–	–	1 (1)	–	–
Breña Alta	28° 39′ 34″	17° 46′ 32″	N	OF	–	–	–	–	–	1 (1)
Tijarafe	28° 41′ 45″	17° 57′ 58″	N	GH	–	–	–	1 (1)	–	–
Puntallana	28° 42′ 59″	17° 44′ 26″	N	2OF/1 GH	–	–	–	3 (3)	–	–
San Andrés	28° 48′ 25″	17° 45′ 47″	N	OF	–	–	–	–	1 (1)	–
Barlovento	28° 50′ 16″	17° 46′ 48″	N	OF	–	–	–	–	2 (2)	–
Gran Canaria										
Arguineguín	27° 46′ 41″	15° 39′ 57″	S	OF	–	–	–	2 (2)	–	–
Vecindario	27° 50′ 28″	15° 25′ 51″	S	GH	1 (1)	–	1 (1)	–	2 (2)	1 (1)
Veneguera	27° 52′ 23″	15° 45′ 37″	S	OF	–	–	2 (2)	–	–	–
Aldea	27° 59′ 13″	15° 47′ 12″	S	GH	–	–	1 (1)	–	–	–
Arucas	28° 07″ 51″	15° 31′ 34″	N	OF	1 (1)	–	–	–	–	1 (1)
Guía	28° 09′ 27″	15° 37′ 31″	N	GH	1 (1)	–	–	–	–	–
Gáldar	28° 10′ 01″	15° 41′ 13″	N	4GH/1OF	1 (1)	–	4 (4)	–	–	–
La Gomera										
La Dama	28° 03′ 17″	17° 18′ 33″	S	GH	1 (1)	–	–	–	–	–
Valle Gran Rey	28° 05′ 33″	17° 20′ 13″	S	OF	–	–	–	–	3 (3)	–
San Sebastián	28° 06′ 26″	17° 08′ 29″	N	GH	–	–	–	–	1 (1)	–
Hermigua	28° 10′ 37″	17° 10′ 59″	N	OF	–	–	–	–	1 (1)	–
El Hierro										
Tacorón	27° 39′ 50″	18° 01′ 03″	S	GH	–	–	–	1 (1)	–	–
Frontera	27° 46′ 52″	18° 00′ 29″	N	GH	–	–	4 (4)	4 (4)	3 (3)	–

average prices during the sampling period were 0.97 €/kg for premium quality, 0.81 €/kg for first class and 0.51€/kg for second class fruit. As it was not possible to determine which quality category damaged bananas would have been assigned to in the absence of *C. chalcites*-induced feeding damage, the losses for each category were based on the average production in each category in the study period, namely 47% in the premium category, 41% for first class and 12% for second class categories.

2.3. Estimated costs of control

The costs derived from *C. chalcites* control in banana were estimated following established methodology (Bielza and Lacasa, 1998). Insecticidal cost involves the costs associated with the purchase of the insecticidal product (product price, application rate, and frequency of treatments) and the implementation costs (labour and time spent).

To calculate the insecticide cost, the prices of the phytosanitary products were obtained from local distributors. The application rates (dose/ha) were those recommended by the product label in banana cultivation, and the frequency of treatments was obtained from interviews described below.

As the implementation costs are variable, different surveys were carried out on the islands by interviewing field technicians and banana growers. A total of 40 interviews were conducted in different areas of the islands, 15 in Tenerife, 10 in La Palma, 9 in Gran Canaria and 6 in El Hierro. The main information sought through this method was focused on the area treated, the type of production system (open-air or mesh-greenhouse), the part of the plant to be treated, the application system, the volume of each treatment, the labour costs (€/hour and €/ha), the dose applied and frequency of treatments.

2.4. Statistical analysis

Data on the prevalence of infestation across years, aspect and seasons were fitted to generalized linear models with a binomial error structure specified in GLIM (Numerical Algorithms Group, 1993). The significance of changes in model deviance were assessed with reference to χ^2 statistics (Crawley, 1993). Fisher's exact test was used to compare the incidence of *C. chalcites* in Gran Canaria because the sample size was small.

Data for the foliar and fruit damage were normalized by arcsine transformation (arcsine $(\sqrt{(x+0.5/100)})$ prior to analysis in order to stabilize variances. Data were subjected to a repeated measures 2-way analysis of variance (repeated measures ANOVA) with islands and seasons as fixed effects, with means compared using Tukey HSD test ($P < 0.05$). Comparisons of year, slope and cropping system were performed by t-tests. Spearman Rank Correlation was used to assess the correlation between foliar and fruit damage.

Finally, to estimate the economic impact of *C. chalcites*, the percentage of discarded banana (by weight) was normalized by arcsine

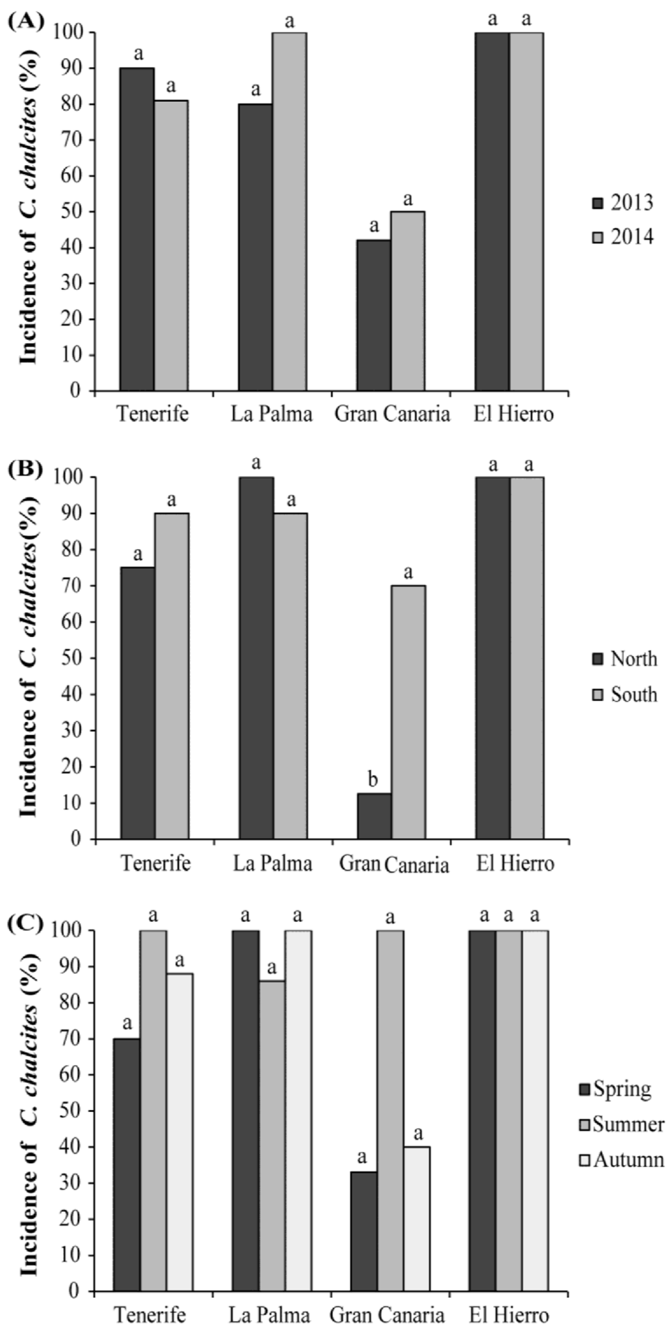

Fig. 1. *C. chalcites* incidence during the two sampling years (A), according to north-facing or south-facing aspect (B) or in function of the seasons (C) on the different islands. Values above columns indicate percentages. Values followed by identical letters did not differ significantly (Fisher's exact test at $P > 0.05$).

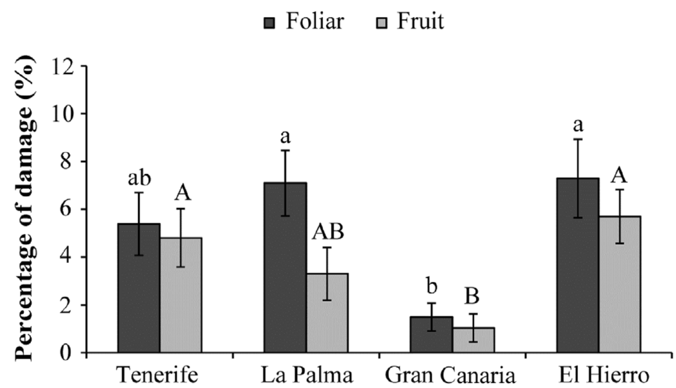

Fig. 2. Mean percentages of foliar and fruit damage after pooling the data from both years. Values followed by identical letters did not differ significantly (ANOVA followed by Tukey's test ($P > 0.05$) for comparisons among islands). Lowercase letters refer to the foliar values and upper case letters fruit values. Vertical lines indicate the standard error.

transformation and analyzed by ANOVA with islands and seasons as fixed effects, with means compared using Tukey HSD test ($P < 0.05$). All analyses were performed using the SPSS Statistics Data Editor v 17.0 (Chicago, IL, USA).

3. Results

3.1. *C. chalcites* incidence and feeding damage

The incidence of *C. chalcites* infestation on the different islands was similar during the two years of the study ($\chi^2 = 2.51$; d.f. = 1; P = 0.11) ranging from 42 to 50% of plots infested on Gran Canaria to 100% of plots infested on El Hierro (Fig. 1A). The incidence of *C. chalcites* in banana plots was similar among plots with a north-facing or a south-facing aspect ($\chi^2 = 2.39$; d.f. = 1; P = 0.12), with the exception of Gran Canaria on which south-facing slopes were more frequently infested than north-facing slopes (Fisher's exact test, P = 0.025) (Fig. 1B). The percentage of *C. chalcites* incidence in function of the seasons did not differ significantly across the islands ($\chi^2 = 5.24$, d.f. = 2, P = 0.07), even for Gran Canaria (Fisher's exact test P = 0.072) (Fig. 1C).

Foliar damage was similar during both years of sampling on Tenerife (t = 1.05; d.f. = 24; P = 0.31), La Palma (t = 0.08; d.f. = 16; P = 0.93), Gran Canaria (t = 0.84; d.f. = 16; P = 0.41) and El Hierro (t = 0.60; d.f. = 10; P = 0.56). Fruit damage was also similar in both years on the islands of Tenerife (t = 1.28; d.f. = 24; P = 0.21), La Palma (t = 0.52; d.f. = 16; P = 0.61), Gran Canaria (t = 0.21; d.f. = 16; P = 0.83) and El Hierro (t = 1.83; d.f. = 10; P = 0.1). Therefore, the data from both years were pooled for subsequent analyses (Fig. 2).

Thus, mean foliar damage evaluated in field surveys over the two-year period was significantly higher in El Hierro (7.3%) and La Palma (7.1%) than in Gran Canaria (1.5%) and Tenerife was intermediate (5.4%) ($F_{3,70} = 5.43$, P = 0.002). Similarly, fruit damage in field surveys was significantly higher in El Hierro (5.7%) and Tenerife (4.8%) than in Gran Canaria (1%) ($F_{3,70} = 4.49$, P = 0.006), whereas La Palma (3.3%) presented an intermediate prevalence of fruit damage (Fig. 2).

Significant interactions occurred between Island and crop aspect (north- and south-facing slopes) for the percentage of foliar and fruit damage (Fig. 3A and B). When comparing north-facing crops, foliar damage was higher in El Hierro and La Palma than in Gran Canaria ($F_{3,32} = 4.55$, P = 0.008), while the damage in Tenerife was intermediate. In contrast, in the south-facing crops, foliar damage did not differ significantly between islands ($F_{3,34} = 1.88$, P = 0.15) (Fig. 3A). Within each island, foliar damage was higher on south-facing slopes in Gran Canaria (t = 2.4, d.f. = 16, P = 0.004), while on the islands of Tenerife (t = 0.5, d.f. = 24, P = 0.53) and La Palma (t = 0.7, d.f. = 16, P = 0.43), no differences were observed for plots situated under different slopes. The effect of slope was not analyzed for El Hierro as just one observation was performed on south-facing crops.

Regarding fruit damage, crops grown on the north-facing slopes of El Hierro were significantly more damaged than on Tenerife and Gran Canaria, whereas damage on La Palma was intermediate ($F_{3,32} = 10.09$, $P < 0.001$). In contrast, fruit damage on south-facing slopes did not differ significantly between the islands ($F_{3,34} = 1.84$; P = 0.16) (Fig. 3B). Fruit damage was significantly higher on south-facing slopes of the islands, on Tenerife (t = 2.7; d.f. = 24; P = 0.022) and Gran Canaria (t = 2.2; d.f. = 16; P = 0.003), whereas aspect had no significant effect on La Palma (t = 0.10; d.f. = 16; P = 0.37).

When comparing islands within each season, El Hierro had

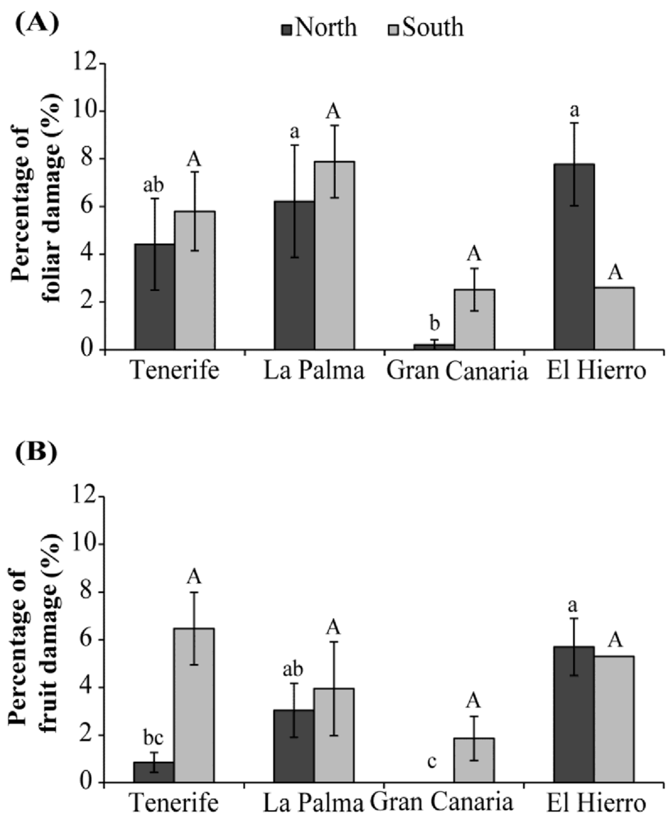

Fig. 3. Percentage of foliar (A) and fruit (B) damage produced by *C. chalcites* in banana crops according to islands and crop aspect (north-facing or south-facing). Values followed by identical letters did not differ significantly (ANOVA followed by Tukey's test at P > 0.05). Lower case letters refer to north values and upper case letters south values. Vertical lines indicate the standard error.

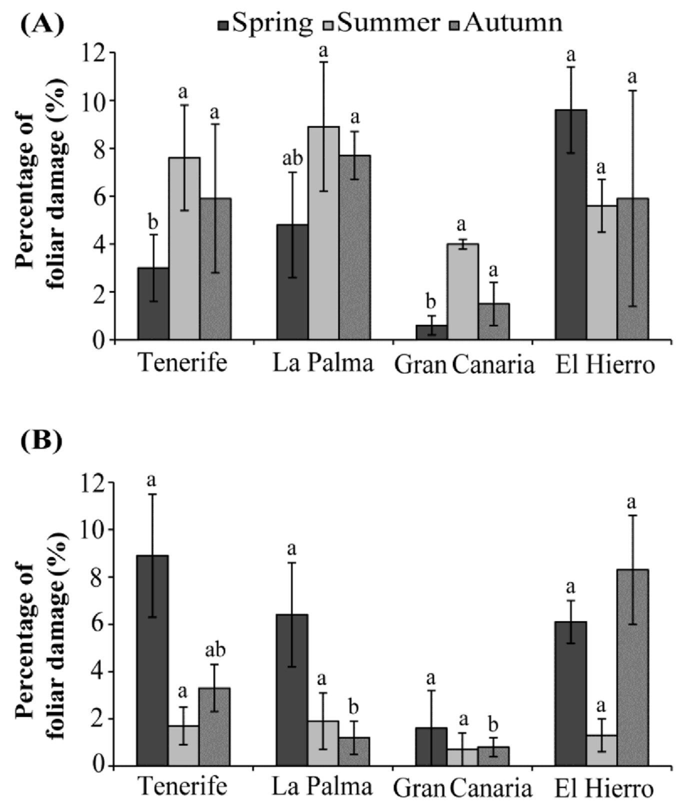

Fig. 4. Percentage of foliar (A) and fruit (B) damage produced by *C. chalcites* in banana crops in the different seasons of the year. Values followed by identical letters did not differ significantly (ANOVA followed by Tukey's test (P > 0.05)). Comparisons were made for each season across the islands. Vertical lines indicate the standard error.

significantly higher foliar damage than Tenerife or Gran Canaria in spring ($F_{3,24} = 4.93$; P = 0.008), whereas La Palma presented intermediate damage. In summer ($F_{3,17} = 0.31$; P = 0.82) and autumn ($F_{3,21} = 2.17$; P = 0.12), foliar damage was similar among all islands (Fig. 4A). Foliar damage in field surveys did not differ significantly between seasons on each island (Tenerife, $F_{2,23} = 1.72$, P = 0.20; La Palma, $F_{2,15} = 1.15$, P = 0.34; Gran Canaria, $F_{2,15} = 2.04$, P = 0.16 and El Hierro, $F_{2,9} = 0.95$, P = 0.42). In contrast, no significant differences were observed for fruit damage between the islands in spring ($F_{3,24} = 2.24$; P = 0.10) and summer ($F_{3,17} = 0.10$; P = 0.96), whereas fruit damage was significantly higher on El Hierro than on La Palma or Gran Canaria in autumn ($F_{3,21} = 7.90$, P = 0.001), and fruit damage on Tenerife was intermediate (Fig. 4B). Fruit damage tended to be highest in spring but this effect was only significant on El Hierro where fruit damage was higher in spring (6.1%) and autumn (8.3%) than in summer (1.3%) ($F_{2,9} = 7.04$, P = 0.014). No significant correlation was found between foliar damage and fruit damage (r = 0.142; Spearman P > 0.05).

Interactions were found between the cropping system (greenhouse or open field) and islands (P < 0.05) for percentage of foliar and fruit damage, therefore, the analysis was performed by island. In Tenerife, foliar damage was similar between cropping systems (t = 0.51, d.f. = 25, P = 0.5) as well as in La Palma (t = 1.25, d.f. = 16, P = 0.41). In Gran Canaria, foliar damage was greater in greenhouse compared to open-field crops (t = 2.0, d.f. = 16, P = 0.006) (Fig. 5A). Fruit damage was similar between open-field and greenhouse crops in Tenerife (t = 1.30, d.f. = 25, P = 0.05) and La Palma (t = 0.5, d.f. = 16, P = 0.37), while it was higher under greenhouse conditions in Gran Canaria (t = 1.3, d.f. = 16, P = 0.014) (Fig. 5B).

3.2. Estimation of economic losses caused by C. chalcites

The weight of bananas that could not be sold due to *C. chalcites* feeding damage was significantly higher on El Hierro (mean weight ± SE: 31.5 ± 8.8 kg damaged bananas in each packing facility, representing 4.2% of lost fruit with respect to the total weight of bananas processed during each 6 h sampling period) compared to Gran Canaria (10.7 ± 7.9 kg, 0.4%) and Tenerife (8.7 ± 5.5 kg, 0.2%), whereas La Palma (27.1 ± 13.1 kg, 1.8%) was intermediate ($F_{3,89} = 4.79$, P = 0.004) (Fig. 6A). Within each island, significantly more bananas were discarded in the spring in La Palma ($F_{2,24} = 5.3$, P = 0.012) and Tenerife ($F_{2,23} = 7.7$, P = 0.003) than during the other seasons, while there were no differences between seasons in Gran Canaria (t = 0.15, d.f. = 18, P = 0.32). In El Hierro, losses also occurred in the spring, but it was not possible to compare damage among seasons due to low numbers of observations (Fig. 6B). Considering the spring period alone, significantly greater weights of bananas were discarded on El Hierro (4.2%) and La Palma (3.8%) compared to those discarded on Gran Canaria (0.3%), whereas an intermediate quantity of bananas was discarded in Tenerife (0.7%) ($F_{3,43} = 4.8$, P = 0.006).

Extrapolating this discarded percentage to the total banana production per year on each island, the total weight of discarded bananas in a year was obtained. Therefore, 350 tonnes of *C. chalcites* damaged fruit was expected to be discarded on Tenerife from a total production of 174,792 tonnes. Similarly, *C. chalcites* damaged fruit was estimated to account for 2369 tonnes on La Palma from a total production of 131,585 tonnes. On Gran Canaria, an estimated 316 tonnes were discarded from a total of 78,935 tonnes and 120 tonnes was discarded on El Hierro from a total production of 2856 tonnes. Therefore, across the four main banana-producing Canary Islands, 3155 tonnes of bananas per year are likely to be discarded due to *C. chalcites* damage.

Taking into account the market price established for this period and

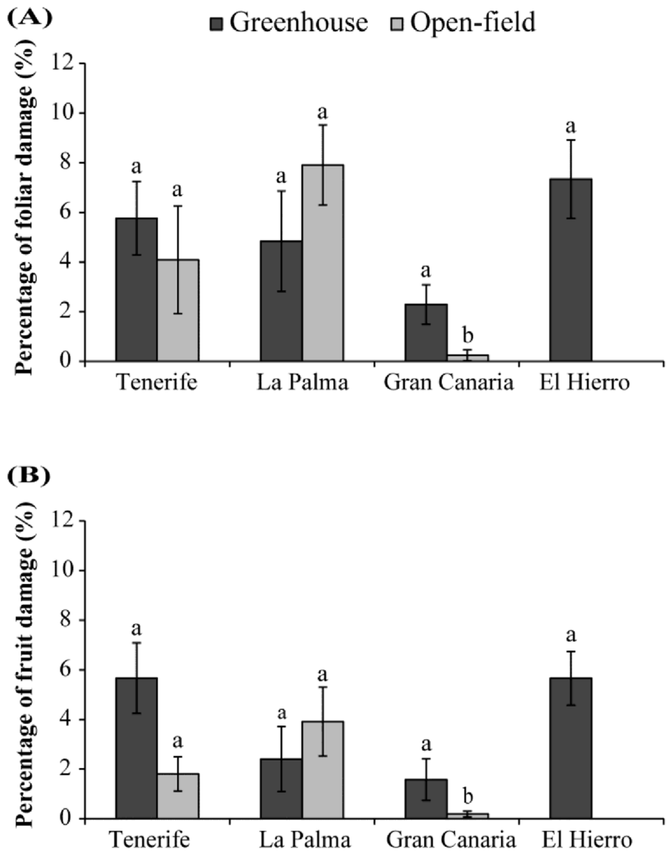

Fig. 5. Percentage of foliar (A) and fruit (B) damage produced by *C. chalcites* in banana crops in the two cropping systems (greenhouse and open-field). Values followed by identical letters did not differ significantly (*t*-test ($P > 0.05$)). Vertical lines indicate the standard error.

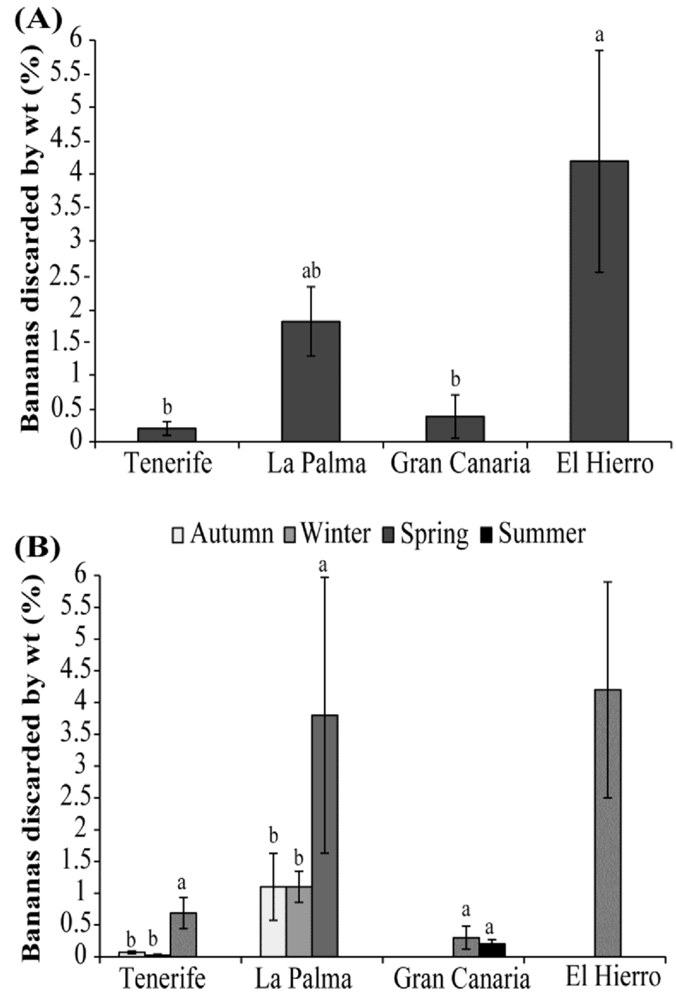

Fig. 6. (A) Mean percentage of bananas by weight (wt) that could not be sold due to *C. chalcites* damage with respect to the total weight of fruit processed in the different processing plants on the islands and (B) percentage of crop losses by weight in the different seasons of the year. Values followed by identical letters did not differ significantly (ANOVA, Tukey's test $P > 0.05$). Comparisons were made for different seasons within each island. Vertical lines indicate the standard error.

the average proportion of fruit that meet quality categories, an estimated 2.68 million euros was lost, of which 1.44 million euros were due to losses in premium class fruit, 1.05 million euros in first class and 193,000 euros in second class fruit (Table 1S). By island, the highest losses were estimated on La Palma (2,011,755 €) followed by Tenerife (297,220 €), Gran Canaria (268,347 €) and El Hierro (101,904 €). Taking into account that the value of total annual production in 2015 was 182 million euros (MAPAMA, 2016), *C. chalcites* fruit feeding damage represented a loss of approximately 1.5% of the overall annual production of saleable fruit.

In relation to the average cultivated area (8975 ha in 2015), *C. chalcites* damage represented approximately 306 €/ha on average. Losses across the islands varied from 73 €/ha to 1665 €/ha (Table 1S). Interestingly, there was a negative relationship between *C. chalcites* induced damage and cultivated area. The most serious losses per hectare were calculated for El Hierro (1665 €/ha), which is the island that has the smallest cultivated area (61.2 ha). On the other islands, estimated losses varied from 663 €/ha over 3033 ha on La Palma, 152 €/ha over 1766 ha on Gran Canaria to 73 €/ha over the 4095 ha of cultivated area on Tenerife.

3.3. Estimating costs of *C. chalcites* control

The results of the interviews with field technicians and growers are summarized in Table 2. Regarding the treatment target or part of the plant to be treated, the whole plant was treated in 26 cases (65%), the treatment was directed at the banana fruits in 8 cases (20%) and small immature plants (< 2 m height) were treated in 6 cases (15%). The volume of treatment depended on plant phenology, so that application volume was 3773 ± 1114 l/ha (mean ± SE) for young plants and 2474 ± 246 l/ha for adult plants, probably because young plants are grown at higher densities than mature plants. In contrast, treatments targeted specifically at developing fruit had a mean application volume of 765 ± 54 l/ha. Treatment of young plants also involved higher labour costs (mean 92 ± 10 €/ha) than whole plants (53 ± 13 €/ha) or applications targeted at the fruit (36 ± 2 €/ha).

Another finding that arose from the interviews was the different products used for *C. chalcites* control. Indoxacarb was most frequently used for *C. chalcites* control (29 cases, 72%), followed by chlorpyrifos (13 cases, 32%), *Bacillus thuringiensis* var. kurstaki (Bt) (8 cases, 20%) and the pyrethroid lambda-cyhalothrin (2 cases, 5%), while the botanical insecticide azadirachtin was used just once (2.5%). The cost of treatments was lowest for the indoxacarb (1.09 €/hl) and Bt (1.33 €/hl) treatments and highest for the azadarachtin treatment (15.14 €/hl), whereas the chlorpyrifos and lambda-cyhalothin treatments were of intermediate cost at 2.51 €/hl and 2.63 €/hl, respectively (Table 2). The overall cost of treatment for each insecticide was calculated from the price per hectolitre multiplied by the volume of treatment (insecticide cost) and added to the labor cost (Table 2).

In most cases (77%), insecticide treatments were performed with only one product, whereas in 23% of cases two products were used in mixtures. More than half of the insecticide treatments (58%) were performed when *C. chalcites* was detected by the presence of larvae or

Table 2
Plant protection products used in *C. chalcites* control, frequency of use, dose, price per 100 L (hl), insecticide cost and total cost of treatment, based on interviews of 40 field technicians and growers performed on the Canary Islands.

Insecticide	Frequency	Price (€)[a] (mean ± SE)	Dose[b]	Price (€/hl) (mean ± SE)	Insecticide cost (€/ha)[c]			Total cost (€/ha)[d]		
					Young	Whole	Fruit	Young	Whole	Fruit
Indoxacarb 30% WG 250 g (Steward)	72.5%	68 ± 6.0	4 g/hl	1.09 ± 0.10	41	27	8	133	80	44
Chlorpirifos 48% SC 1 l (Dursban)	32.5%	13 ± 0.6	200 ml/hl	2.51 ± 0.12	95	62	19	187	115	55
Bacillus thuringiensis kurstaki 32% WG 1 kg (Dipel)	20%	27 ± 0.9	50 g/hl	1.33 ± 0.04	50	33	10	142	86	46
Lambda-cyhalothrin 2.5 WG 1 kg (Karate king)	5%	33 ± 5.0	80 g/hl	2.63 ± 0.36	99	65	20	191	118	56
Azadirachtin 3.2% SC (Align)	2.5%	101 ± 9.0	150 ml/hl	15.14 ± 1.32	572	375	116	664	428	152

[a] Price of product obtained from distributors.
[b] Dose recommended by the product label.
[c] Insecticide cost is related with the volume of treatment used, for young plant was 3773 ± 1114 l/ha, for whole plant 2474 ± 246 l/ha and for the bunch 765 ± 54 l/ha.
[d] Total cost represented the summarized of the insecticide cost and the labour cost, which was estimated for young plant 92 ± 10 €/ha, for whole plant 53 ± 13 €/ha and for the bunch 36 ± 2 €/ha.

damage to leaves or fruit that varied according to island and location. The frequency of treatments varied between 0 and more than 3 applications per year, with three treatments per cropping cycle being the most common (36%) (data not shown).

Considering that the most frequently used pesticide was indoxacarb, that an average of three treatments were usually required during the crop cycle and that the main treatment target was the whole plant, the total cost of *C. chalcites* control during a cycle of banana cultivation in the Canary Islands would likely average 240 €/ha. The value of average production per hectare (based on an average production of 44 tonnes/ha), taking into account the different quality categories and their market prices, was estimated to be 37,365 €. Therefore, the average cost of control of *C. chalcites* with indoxacarb represents approximately 0.64% of the overall crop value, taking into account that young plants do not mature and begin to produce fruit until approximately 9 months of age.

4. Discussion

Estimation of agricultural losses is key for the rational management of *C. chalcites* and for evaluation of the effectiveness of current plant protection practices in banana crops in the Canary Islands. Our study revealed that control of *C. chalcites* mainly involves applications of indoxacarb, chlorpyrifos or Bt insecticide. The costs associated with insecticide purchase and application should be included in IPM-based decision-making, particularly when considering the economic impact of the pest in banana crops. Therefore, the present study aimed to determine the incidence, damage levels, production losses due to direct damage and the treatment costs related to *C. chalcites* control.

Feeding damage by *C. chalcites* was most severe on the islands of El Hierro, La Palma and Tenerife, whereas *C. chalcites* was of minor importance on Gran Canaria. Although previously considered a minor pest that mostly fed on leaves, fruit damage by *C. chalcites* had become generalized by 2002 in El Hierro crops. This was followed by fruit damage reported in banana plantations located in the south of La Palma, later in southern Tenerife, and finally in 2012 in Gran Canaria (Del Pino et al., 2011; Perera and Molina. 2007). One of the factors that may have contributed to the resurgence of *C. chalcites* as an emerging pest could be the elimination of authorized insecticides in banana crops, from 24 active compounds in 2006 to 12 compounds in 2014 (López-Cepero, 2015). Nonetheless, the reasons behind the changes in feeding behavior directed towards fruit are unclear and, given the highly mobile nature of this pest, seem unlikely to reflect behavioral changes in an isolated local pest population.

The prevalence of *C. chalcites* infestations and feeding damage on southern slopes is likely influenced by the cropping system established on each slope, as mesh-built greenhouses are more common on south-facing slopes that are warmer and dryer than the north-facing slopes. In general, damage by *C. chalcites* tends to be greater in banana crops in greenhouses than in the open-field. The mesh greenhouses protect banana crops from onshore winds (Galán-Saúco, 1992; Robinson and Galán-Saúco, 2010), but may also reduce the movement of natural enemies (Del Pino et al., 2013; Polaszek et al., 2012). In addition, temperatures are higher on the south-facing slopes (Table 2S), which likely favor the development of *C. chalcites*. Differences in the maximum and minimum temperatures between slopes can reach up to five degrees, especially in Gran Canaria (Table 2S). These differences in temperature can influence the duration of the biological cycle of the pest, shortening it in case of the higher temperatures (Barrionuevo et al., 2012; Danks, 2000; Mironidis and Savopoulou-Soultani, 2008), which is probably why more generations of *C. chalcites* can occur on the crops grown on south-facing slopes during the year.

In banana crops grown under mesh on south-facing slopes, *C. chalcites* generations follow one another throughout the year with no diapause (Del Pino et al., 2011; Domínguez et al., 2012; García et al., 1992; Perera and Molina, 2007), unlike the generational patterns observed in glasshouses in northern Europe (van de Veire, 1993; Vos and Rutten, 1995). However, *C. chalcites* has two predominant flights during the year, one in spring (May–June) and the other in autumn (September–October) (Bernal et al., 2013; Del Pino et al., 2011). Adults are able to migrate over great distances from northern Europe to southern Africa (García et al., 1992). For example, Spitzer and Jaros (2004) observed a mass flight of immigrant adults on the southeast coast of Tenerife in the spring. According to the results presented in this study, no large differences among season occurred in foliar and fruit damage. Larvae of *C. chalcites* feed preferentially on young leaves, and particularly on young plants. Larvae may attack the banana crop from transplanting until fruit maturity, but the most sensitive growing periods are from transplanting to the first foliar stages and flowering and fruiting, which occur during the main peak flight in the spring (Del Pino et al., 2011; Galán-Saúco, 1992; Robinson and Galán-Saúco, 2010). On young plants, larvae produce damage by perforating leaves (Del Pino et al., 2011; Domínguez et al., 2012; Perera and Molina, 2007; Simón et al., 2015; Vilardebo and Guérout, 1964). Planting of young banana plants is usually done during summer periods and, although the adult flight is less prevalent compared with the spring, the presence of individuals might have consequences for plantations of young plants, as the crop is highly attractive to the pest at this time. However, in the present study, the foliar damage produced by *C. chalcites* on young plants is unlikely to have had a substantial effect on final crop production, as major defoliation would be needed to cause crop losses. Previous studies showed that complete defoliation of the plant crop at the 5-leaf stage had no effect on the weight of bunches but delayed harvest, whereas complete defoliation when the plant had 35 leaves reduced the production of fruit by about 30% (Turner and Hunt, 1987). Similarly, *C. chalcites* feeding damage to the leaves of mature plants was negligible and was unlikely to have had a detectable effect on fruit production, whereas direct damage to fruit had a clear and important influence on the commercial value of fruit. Damage to fruit in the spring is particularly important as it coincides with the development of the fruit after flowering which is the most susceptible period for determining the quantity and quality of the harvested fruit (Del Pino et al., 2011; Galán-Saúco, 1992; Robinson and Galán-Saúco, 2010).

Therefore, monitoring and controlling *C. chalcites* during the spring season would be of particular value for the effective protection of developing fruit. Crop protection strategies, based on preventing quantitative crop losses rather than pest outbreaks, represent a promising approach to rationalize pesticide use. However, in the present study, no correlation was found between foliar damage and fruit damage in banana crops in the Canary Islands. Therefore, foliar damage observed at a given moment is unlikely to be a useful predictor of the impact of *C. chalcites* on marketable yield, and so, alternative predictors should be investigated.

Observations on banana damage registered in packaging plants agreed with the results obtained through field surveys on fruit damage. For example, on El Hierro where 5.7% of fruit damage was observed in field surveys, losses of fruit in packaging plants was of similar magnitude (4.2%), whereas in Gran Canaria (0.4%) and Tenerife (0.2%) fewer losses were registered due to direct damage to fruit. Although 4.8% of fruit damage was registered on Tenerife in the field, just 0.2% of fruit was discarded, which suggests that workers at this processing facility used different criteria for rejecting superficially damaged fruit. Previous studies with *C. chalcites* in banana crops in the Canary Islands estimated average losses of banana production at 9.4% of the total bunch (Del Pino et al., 2011; Domínguez et al., 2012). However, these estimates were performed based on small numbers of plants in controlled conditions, therefore losses may have been overstated. In the present study, fruit loss estimates were between 0.2% and 4.2%. It may also be that some packaging plants lower the quality category depending on the grade of *C. chalcites* damage, which carries an associated reduction in value but does not necessarily prevent the sale of the damaged bananas. It was not possible to estimate *C. chalcites* related changes in fruit quality classifications as only the weight of discarded fruit was measured. The same level of pest damage can cause different yield losses because quality standards vary between banana growing producer associations. These quality standards for packaging bananas consider both the presence of insects on the fruit and superficial appearance. A similar situation was observed on tomato crops in southern Spain, where damage levels tolerated for processing tomatoes largely depended on criteria established by the tomato processing industry and varied according to final use of goods (e.g., juice, past, canning, etc.), cropping years, annual production and especially market conditions (Torres-Vila et al., 2003). Taking into account the percentage of the discarded bananas and the area cultivated on the different islands, we estimated that on average *C. chalcites* is likely to be responsible for annual losses of approximately 2.68 million euros despite the adoption of control measures.

Among three main insecticides commonly in banana crops, indoxacarb and *Bacillus thuringiensis* are biorational products, whereas chlorpyrifos is a broad-spectrum organophosphate pesticide. Our results also highlighted that the volumes used to apply treatments were highly variable, as were the labour costs to treat one hectare of crop. This is mainly due to the treatment system used and the time spent in applying treatments. For example, in some areas of the islands, such as La Palma, bananas are grown in small, highly fragmented plots, where tractor mounted spray machinery is not used. This results in an increased volume and time required to treat the crop. Indeed, 82% of banana crops are grown on small farms of less than 1 ha. Therefore, low levels of mechanization tend to increase the overall cost of production.

On El Hierro and La Palma, losses due to *C. chalcites* damage to fruit exceed the cost of insecticide purchase and application, whereas on Tenerife and Gran Canaria, the losses due to *C. chalcites* damage were lower than the control costs. It is necessary to design IPM programs that consider different aspects that could improve the ratio of production costs to crop yields, particularly those related to treatment thresholds. Establishing treatment thresholds is complex, but necessary to make decisions in IPM systems. Banana growers and field technicians currently use observations of feeding damage or evidence of larval infestations in their plantations as the main criteria for implementing control measures against *C. chalcites*, although the cost-benefit relationship of insecticide treatments remains to be determined across a range of pest densities and phenological stages of plant development and fruiting. Finally, continuous use of a single dominant insecticide to control *C. chalcites,* as occurs on the Canary Islands, is likely to favor the development of resistance. As such, new insecticides are required for use in rotation with the handful of authorized compounds. Natural enemies such as the egg parasitoid *Trichogramma achaeae* Nagaraja and Nagarkatti, 1970 (Polaszek et al., 2012; Del Pino et al., 2013, 2015) can contribute to the biological control of this pest but are insufficient to control pest populations below economic thresholds, so additional methods are required (Del Pino et al., 2011). Among these, the nucleopolyhedrovirus of *C. chalcites* (ChchNPV) has been proven to be a highly effective control agent (Bernal et al., 2011; Simón et al., 2015). Experiments are in progress to determine the efficacy of this virus-based insecticide in commercial banana crops in comparison with the other authorized products.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cropro.2018.02.020.

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