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CONSERVATION

PESTICIDES AND THEIR IMPACT ON ENTOMOFAUNA IN ANDEAN FARMERS' FIELDS IN ECUADOR

PESTICIDAS Y SU IMPACTO SOBRE LA ENTOMOFAUNA EN FINCAS DE AGRICULTORES ANDINOS DE ECUADOR

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Abstract

Ignorance of the rational use of insecticides leads farmers in developing countries such as Ecuador to exceed the limit of permitted applications. In addition, little is known about the effect of insecticides on entomofauna of *Lupinus mutabilis* (lupine). This study aims to analyze the effect of insecticides on pests and beneficial insects, with special emphasis on pollinators, without neglecting the effect on crop yield. The entomofauna associated with Andean Lupin was used as a reference. Seventy-nine agricultural fields were evaluated in Cotopaxi-Ecuador, with the treatments with chemicals, without chemicals, and without any control. Once the experiment was presented to the participating group, the farmers chose the management treatment for their fields with recommendations from the researchers. For insect monitoring, yellow sticky and plate traps were used to obtain variables of insect abundance and diversity. The use and application of pesticides was recorded using surveys developed with Survey 123. The results showed that the application of insecticides was not always effective in controlling the pests studied. In addition, the treatments evaluated had different effects according to the type of insect pollinator analyzed. On the other hand, the study also showed that certain pests, especially borers, could induce a positive response (70% more flowers) that can actually benefit the final yield. These results suggest that pest controls for this crop should be more targeted and carried out before flowering to avoid causing damage to pollinators and borers, as well as natural enemies of pests.

Keywords: lupin, insecticides, pollinators, yield, entomofauna.

Resumen

El desconocimiento del uso racional de insecticidas conlleva a que agricultores de países en desarrollo como Ecuador sobrepasen el límite de aplicaciones permitidas. Además, poco se conoce del efecto que tienen los insecticidas sobre la entomofauna de *Lupinus mutabilis* (chocho). Este estudio busca analizar el efecto de los insecticidas sobre plagas e insectos benéficos con especial énfasis en polinizadores, sin descuidar el efecto sobre el rendimiento del cultivo. Se tomó como referencia la entomofauna asociada al cultivo de chocho. Se evaluaron 79 campos agrícolas en Cotopaxi-Ecuador, con tratamientos con químico, sin químico y sin ningún control. Una vez socializado el experimento, los agricultores eligieron el manejo para sus campos con las recomendaciones de los investigadores. Para el monitoreo de insectos se usaron trampas pegantes y de plato de color amarillo. Se obtuvieron variables de abundancia y diversidad de insectos. El uso y aplicación de plaguicidas se registró usando encuestas desarrolladas con Survey 123. Los resultados muestran que la aplicación de insecticidas no siempre fue efectiva en el control de las plagas analizadas. Además, los tratamientos evaluados tuvieron efectos distintos según el tipo de insecto polinizador analizado. Por otro lado, se observó que ciertas plagas, en especial barrenadores podrían inducir un efecto de respuesta positivo (70 % más de flores) que beneficiaría el rendimiento final. Estos resultados podrían sugerir que los controles de plagas para este cultivo deberían ser más dirigidos y realizarse antes de la floración, esto evitaría causar daños a polinizadores, barrenadores y probablemente enemigos naturales de plagas.

Palabras clave: chocho, insecticidas, polinizadores, rendimiento, entomofauna.

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1 Introduction

The use of pesticides is a global practice, predominantly present in low-income countries. Factors such as lack of training, low education levels among farmers, limited alternatives to pesticides, and the influence of vendors are some of the reasons behind this (Berni et al., 2021; Jallow et al., 2017; Khan et al., 2015). According to the FAO (2017), global pesticide consumption reached over 4.11 million tons that year. FAO data shows that in the last 20 years, countries like Italy, France, and Japan have reduced pesticide use by an average of 36%. In contrast, countries such as Malawi, Bangladesh, and Ethiopia have seen a 1325% increase in demand. In Latin America, more than 5 kg of pesticide per hectare are used, while in countries like Ecuador, pesticide application increased by over 1500% between 1990 and 2017 (FAO, 2017). Most studies place the blame for pesticide misuse on farmers (Damte and Tabor, 2015; Mengistie et al., 2017). The lack of basic understanding and an integrated perspective on pests contributes to this "misuse" by farmers (Wyckhuys et al., 2019), without accounting for external influencing factors such as government actions, universities, NGOs, and private companies (Pan et al., 2021). However, at the individual level, pesticide decision-making and resistance management are not solely the responsibility of farmers (Gould et al., 2018); all actors in the supply and consumption chain share this responsibility. In fact, farmers themselves acknowledge being blamed for the decline in insects, biodiversity loss, and pesticide overuse. However, they also consider this a holistic problem that should address multiple causes (Busse et al., 2021).

Pesticide application has numerous impacts, including soil contamination, human health risks, and environmental damage (Budzinski and Couderchet, 2018). In fact, pesticide use is one of the most damaging agricultural practices for agrobiodiversity (Mengistie et al., 2017). Studies confirm the negative impact of insecticides on entomofauna, showing declines and/or losses (Catarino et al., 2019; Goulson, 2019). Scientists attribute the most extensive harmful effects to insecticide use (Chemnitz, 2022). Intensive insecticide use is believed to accelerate pest adaptation while making beneficial insects more vulnerable (Potts et al., 2010; Chivian and Bernstein, 2015). For example, the synergy of IBE fungicides and neonicotinoids has caused higher mortality rates in solitary bees *Osmia lignaria*, the bumblebee *Bombus terrestres*, and *Apis mellifera* (Botías and Sánchez-Bayo, 2018). This points to a global crisis in the abundance, diversity, and biomass of insects, particularly pollinators, caused in part by anthropogenic activities in industrialized agricultural landscapes (Forister et al., 2019).

It is estimated that 35% of global food production depends on animal pollination (Klein et al., 2007; Sawe et al., 2020). In fact, between 5% and 8% of global crop production would be lost without insect pollination (Aizen et al., 2009). Economically, agricultural production resulting from animal pollination is valued between $ 235 and $ 577 billion (Sawe et al., 2020). The detrimental effect of pesticides on beneficial entomofauna, specifically pollinators, and its impact on final crop yield has been well documented (Pacífico da Silva et al., 2015; Stanley et al., 2015; de Oliveira et al., 2019). Understanding the composition of entomofauna and their interactions could help improve farmers' knowledge and change their agricultural practices (Magrach et al., 2019).

Combining many elements such as biological control, inter- and intraspecific botanical diversity, synthetic volatile compounds, and induced defense, Integrated Pest Management (IPM) has been one of the most commonly used strategies (Stenberg, 2017). However, IPM has not traditionally considered insects like pollinators, which are also affected by agricultural practices. Consequently, there is a demonstrated need to incorporate strategies that protect pollinators within IPM to reduce their exposure to pesticides (Egan et al., 2020). These authors have proposed transitioning from IPM to IPPM (the second "P" for pollinators).

This approach was integrated into the representation of the interrelationships among the "4P": pesticides, pests, pollinators, and productivity (Figure 1). Pesticides in agriculture are used to control pests (Figure 1a), given their negative impact on productivity (Figure 1b). For many farmers, the use of pesticides is seen as necessary to improve (or prevent the decline of) crop productivity (Figure 1c). Similarly to pests, pesticides generally have a negative effect on pollinators (Figure 1d). Depending on the crop, pollinators can have a neutral or positive effect on productivity (Figure 1e). These relationships demonstrate the need to consider both pest and beneficial insects when evaluating the impact of insecticides on crop productivity.

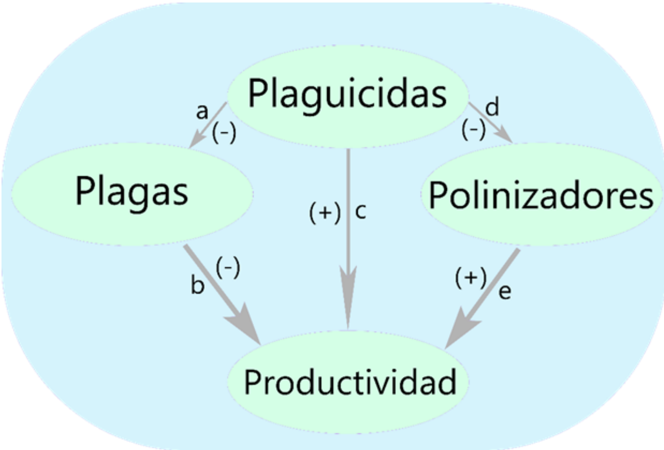

Figure 1. Relationships between the effect of pesticide use on entomofauna and productivity. Figure modified from Struelens et al. (2021).

It is interesting to analyze the transition from IPM to IPPM in an agricultural system where these relationships are represented. In a previous study, Struelens et al. (2021) reported that in Ecuador, insecticide applications affect entomofauna in small-scale Andean farmers' *Lupinus mutabilis* Sweet (chocho) systems. These authors found a significant impact on reducing pollinators due to the number of pesticide applications ($p = 0.021$; path coefficient = -0.892), without a clear reduction in pest populations. However, these conclusions are based on a limited number of fields (fewer than 20 in total), and the relationships between insecticides, pests, pollinators, and crops need further exploration. Although chocho is a self-pollinating plant, its production quality can significantly depend on insect pollinators. Therefore, it is an interesting crop model to analyze the combined effects of insecticides and their impact on entomofauna. Cowling et al. (1998) reported a cross-pollination rate of 4 to 11%, while Caligari et al. (2000) found an outcrossing rate of up to 58.8% in their experiments. Struelens et al. (2021) reported a 10.5% increase in the number of chocho seeds due to visits from pollinating insects.

Chocho is cultivated in several Andean countries. In Ecuador, the main production areas are Cotopaxi, Chimborazo, Pichincha, and Imbabura (SINAGAP, 2014). Its seeds are rich in protein (41-51%) and essential fatty acids (3-14%) (Nicklin et al., 2006). Its symbiosis with the bacterium *Bradyrhizobium* fixes atmospheric nitrogen (between 30 and 70 kg of N/ha), enriching the soil (Alandia, 2018).

However, in Ecuador, agricultural intensification of this crop has been accompanied by an increase in phytosanitary issues, primarily herbivore attacks (Caicedo and Peralta, 2000). In 2015, approximately 7825.59 ha of chocho were planted, with a trend of increasing acreage in subsequent years (INEC, 2015). Although there are few reports and studies on pests in the area, previous surveys by the authors mainly report borers, such as the stem borer (Agromyzidae) and the shoot fly (Anthomyiidae), which are present throughout almost the entire phenological cycle of the crop (Mina et al., 2017). Interestingly, the attack of this pest could suggest increased growth of reproductive organs in chocho, known as an overcompensation effect (Struelens et al., 2021). García and Eubanks (2019) document 86 studies showing examples of overcompensation in response to insect herbivory across 67 plant species representing 26 families.

Insecticide application is often the first, main, and sometimes the only option for Ecuadorian farmers to control pests. A common practice is to mix several pesticides into "cocktails". Sherwood et al. (2005), for example, reported that farmers mixed up to seven products in one "brew", sometimes with the same active ingredient or mechanism of control. In theory, these cocktails save time and labor while increasing efficacy in controlling pests and diseases. However, without clear information on the chemical labels, mixing these products is risky (Mengistie et al., 2017). Pesticide mixtures are a particular concern for human health due to their potential synergistic effects on toxicity. Pesticide mixtures with the same mode of action (MoA) often exhibit additive effects, while those with different MoAs produce effects that are difficult to predict (Hernández et al., 2017). In Ecuador, the problem is exacerbated as the government reports that many of the foods consumed exceed the Maximum Residue Limits (MRL) for pesticides allowed for human consumption.

This study is designed to address three main questions:

(i) How does insecticide use affect pests and pollinators (relationships a and d in Figure 1)?

(ii) Does insecticide use and its impact on entomofauna affect crop yields (relationships b, c in Figure 1)?

(iii) What is the relationship between the level of major pests (borers) and chocho yield (relationship d in Figure 1)?

2 Materials and Methods

2.1 Study sites

The study was conducted in 79 farmers' fields between January and November 2021 in the central-northern highlands of Ecuador (Figure 2). The fields were located in the parishes of Alaquez, Cochapamba, Cusubamba, Eloy Alfaro, Guaytacama, Juan Montalvo, La Matriz, and Pujilí (Table 1).

The study areas and farmers were selected based on: i) Levels of intensification in the agricultural landscape (planting density and/or number of species present in a given area); ii) Agricultural practices (e.g., use or non-use of insecticides); iii) Previous research and training work with farmers in the area; and iv) The farmers' interest in participating in the research.

2.2 Study Desing

Three activities were carried out. The first was the monitoring of insecticide applications in farmers' fields, the second was the monitoring of insect populations, and the third was the study of yield variability.

2.2.1 Recording of Insecticide Applications in Farmers' Fields

Two treatments were initially established: i) With chemicals; fields with synthetic chemical insecticide applications, and ii) Without chemicals; fields with organic insecticide applications. However, fields were also identified where farmers applied no pest control. Ultimately, 39 fields were designated as chemical, 34 as non-chemical, and 6 as no control.

Each farmer chose the treatment to apply, including irrigation, weeding, and the frequency of pest control measures, all financed by the farmers themselves. In all fields, seeds of the chocho variety INIAP-450 Andino were used, disinfected with the chemical recommended and used by local technicians (Tiabendazole + Thiamethoxam). Non-chemical fields used organic-biological strategies such as mineral broths and plant extracts, provided by the farmers and the local university. For the chemical treatments, active ingredients commonly used by farmers were applied (Table 2).

70 % of the farmers who applied chemical treatments used organophosphate and pyrethroid insecticides, with a range of 1 to 4 applications before the flowering stage. On the other hand, 95 % of the fields without chemical treatments used mineral broths and plant extracts (Table 2).

2.2.2 Data Collection

Data on the use and application of chemical products (active ingredient, dosage, frequency of application) were collected through surveys. The study was authorized by the Research Ethics Committee (CEISH) of the Pontificia Universidad Católica del Ecuador (PUCE). Each farmer signed an informed consent form regarding the research activities.

Table 1. Bioclimatic characteristics and treatments applied at the study sites, Cotopaxi 2021.

	Sites	Alaquez	Carrillo	Chan	Cuturivi	Guaytacama	La Merced	Cachipata	Yugshiloma	Total fields evaluated
	Average size of evaluated fields evaluados (m^2)	1850	1387	2125	985	1218	2367	2944	846	
	Main crops	Bean, fava bean, maize	Maize	Pea, bean	Pea, barley, potato	Pea, bean, maize	Maize	Maize, potato	Maize	
Bioclimatic characteristics	Altitude (masl)	3044	3032	2918	3503	2948	2950	3336	2900	
	Average precipitation during monitoring days (mm/day)	8.67	7.88	8.15	10.22	7.68	8.44	8.9	9.75	
	Temperature (°C)	12	11	13	11	11	13	10	11	
Number of treatments	With chemicals	4	6	1	13	5	2	9	2	42
	Chemical free	8	4	2	6	6	1	1	3	31
	No pest control	2		1	1	1	1	0	0	6

In addition to workshops, regular visits and monitoring of each experimental field were conducted. During these workshops, information about the experiment's activities was provided, and each farmer was responsible for applying their chosen treatment (Figure 3E). In-person sessions were held between March and November 2021, following a preestablished biosecurity protocol due to the pandemic.

2.2.3 Monitoring of Insect Populations in Farmers' Fields

Sticky traps and plate traps were used to capture flying insects reported as entomofauna associated with chocho (*Lupinus mutabilis*) (Mina et al., 2017). Yellow plastic sticky traps, A4 size (21 × 29.7 cm) (Ali et al., 2019), were used to sample pest insects and placed at crop height (Figure 3A). The number of traps and their distribution were based on the field's area, with one trap per 1000 m^2 (Heinz et al., 1992; Willett et al., 2020).

Sticky traps were placed 10 to 12 weeks after planting and were left in the field once for 72 hours (Shah et al., 2020). To analyze the effect of insecticides on pests, two insect species identified as pests at this crop stage were selected: i) the shoot borer (Diptera/Anthomyiidae, possibly *Lasiomma* sp. see (Struelens et al., 2021)) (Figure 3C) and ii) the black lady beetle (Coleoptera/Melyridae, *Astylus bourgeoisi*). A third pest, Agromyzidae (possibly *Liriomyza* sp.), was recorded during destructive sampling.

To record pollinating insects, yellow plate traps were placed at flower height (Figure 3B). Each trap contained 200 mL of water and 5 mL of neutral liquid soap (Saunders and Luck, 2013; Padron et al., 2021). Traps were collected after 72 hours (Shah et al., 2020), and the insects were preserved in sealed jars with 70% alcohol for later morphological identification. Insect identification was supported by taxonomic keys and the citizen science tool "iNaturalist" (Inaturalist, 2022).

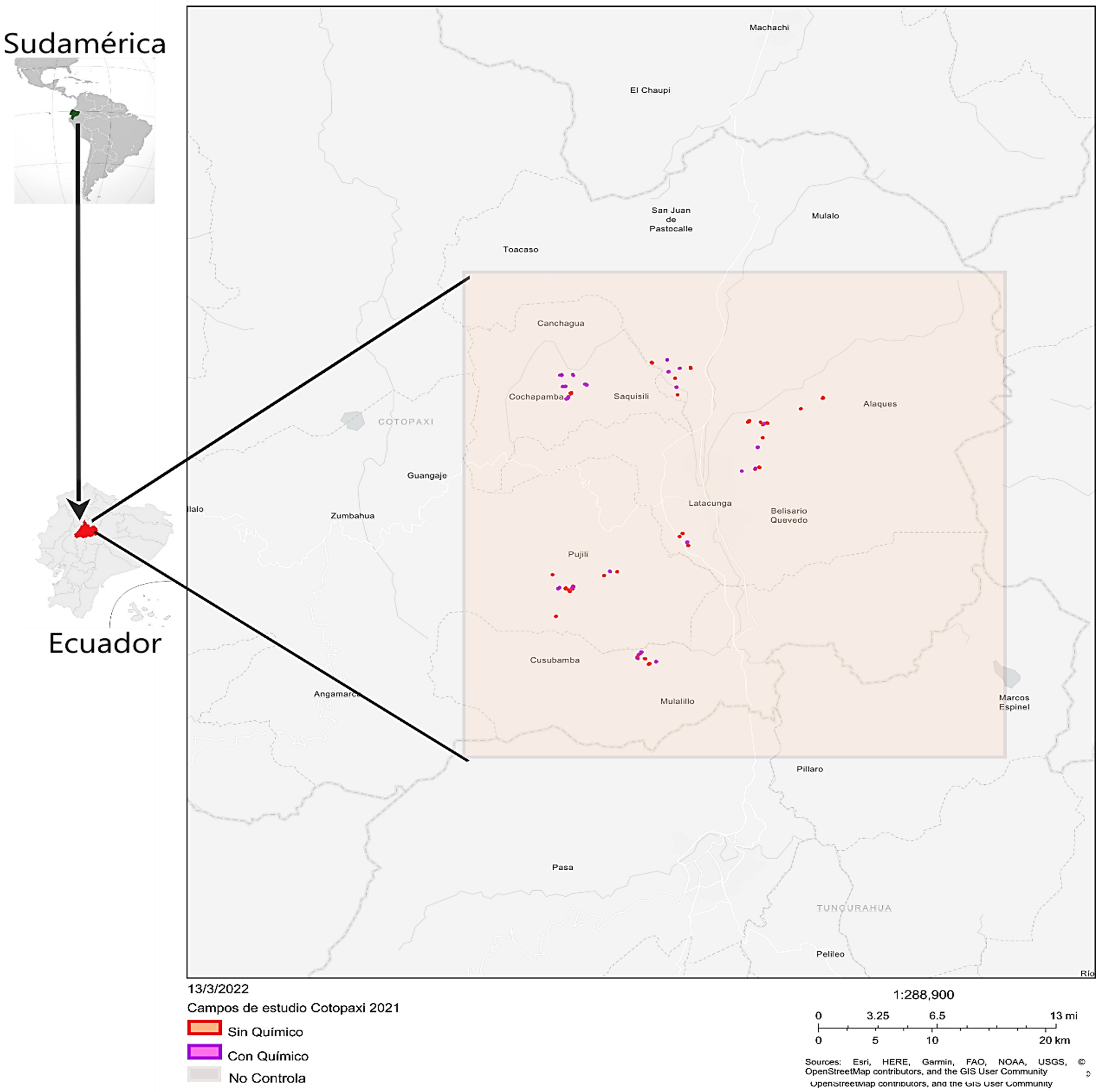

Figure 2. Continental and regional location of the study sites in the Ecuadorian highlands. Distribution of experimental fields according to the applied treatment.

2.3 Recording Variables Related to Damage and Yield

Additionally, damage levels were evaluated by marking 10 plants per field during the vegetative stage for destructive sampling. The height of each plant in reference to the central stem and the number of branches were recorded. These variables are related to the plants' response to the characteristic attack of the borers studied (Struelens et al., 2021). Height was measured in centimeters from the base of the stem to the apex of the central axis. The number of branches was recorded by counting those with reproductive organs (pods and/or flowers) (Garibaldi et al., 2016). These variables were complemented by the abundance of three pests found during destructive sampling: i) shoot borer (Diptera/Anthomyiidae), ii) stem borer (Diptera/Agromyzidae), and iii) moths (Lepidoptera).

Table 2. Treatments used by farmers for insect pest control, Cotopaxi 2021.

	Insect to control	**Chemical treatment Chemical group (GQ) Toxicological class (CT) Mode of action (MA)**	**Chemical-free treatment**
SEEDING	*Delia platura* *Agrotis* sp. *Agriotes* sp.	GQ: Oxime carbamates CT: Ib Highly hazardous MA: Cholinesterase inhibitors	Neem Oil Organic Insecticide 2-2-1 (ginger + chili + garlic) Microbes with Bitter Herb Extracts
		GQ: Pyrethroids and Pyrethrins CT: II Moderately hazardous MA: Insecticidal activity by contact and ingestion, affecting the nervous system	
		GQ: Organophosphates CT: II Slightly hazardous MA: hazardous inhibitor	
		GQ: Organophosphates CT: III Slightly hazardous MA: Acetylcholinesterase inhibitor	
VEGETATIVE STAGE	*Lasiomma* sp. *Liriomyza* sp.	GQ: Neonicotinoids + Phenylpyrazoles (Fiproles) CT: II Moderately hazardous MA: Fipronil, blocks the effect of the GABA (γ-aminobutyric acid) neurotransmitter	Application of Lime Sulfur Sprays Application of Ash Sprays Foliar Fertilizers (Amino Acids)
		GQ: Nereistoxin analogs CT: II Moderately hazardous MA: Stomach and contact action insecticide	

2.4 Data Analysis

Comparisons were made based on the treatment applied by the farmer during the crop cycle. Differences in pest and pollinator abundances between each type of treatment were analyzed using an Analysis of Variance (ANOVA). For pest insects (*Astylus bourgeoisi* and Anthomyiidae), sticky trap counts were used, while for Agromyzidae and pollinators, plate trap counts were used.

The nine most abundant groups of flower-visiting insects recorded across the 79 fields were selected. The effect of the treatments on crop yield, as reported by farmers after harvest, was also evaluated.

In addition to analyzing the impact of insecticides on pests, pollinators, and productivity, the relationship between pests and plant productivity (relationship d in Figure 1) was analyzed. A Productivity Index (PI) was created by summing the flowers and pods of each plant; this value was divided by the number of plants evaluated in each field.

In the 10 plants where productivity was assessed, the total number of borers was also counted through destructive sampling. All larvae of Anthomyiidae, Agromyzidae, and moths were summed. These counts were compared to the productivity index obtained for each field using a non-linear Poisson model. To fit the data to a linear model, a logarithmic transformation (Log +1) was performed for normal distribution and homoscedasticity of variance. All statistical analyses were conducted using the Past 4 project software (Hammer et al., 2001) and R v1.3.959 software (R Core Team 2020).

Figure 3. Methods used in this study (a) sticky traps, (b) plate traps, (c) shoot borer fly (Anthomyiidae/pest), (d) *Eristalis tenax* (Syrphidae/pollinator), (e) farmer applying pest control treatments.

3 Results

Abundance and Diversity of Sampled Entomofauna

In this experiment, 13 morphospecies of insects associated with chocho fields were identified. These were classified into two functional groups: pests and pollinators, either direct or indirect. Four orders and 12 families of insects were identified from a total of approximately 12,000 individuals collected. The order with the highest abundance was Diptera, accounting for 74 %, followed by Coleoptera at 18 %, and the remaining 8 % were Hymenoptera and Lepidoptera. The following are the main results that help address the questions posed in this study.

3.1 Effect of Pesticides on Pests, Pollinators, and Yield

The treatments applied showed variability in the response of the three pest insects analyzed. In all three cases, the "no control"treatment (no application of any pest control) appeared to have the lowest pest abundance. On the other hand, for *A. bourgeoisi* and Agromyzidae, there was a slight trend toward lower abundance in the "non-chemical", a trend not observed for Anthomyiidae. However, statistically, no significant effects of the treatments on the abundance of the three pests were found (p >0.05, Figure 4).

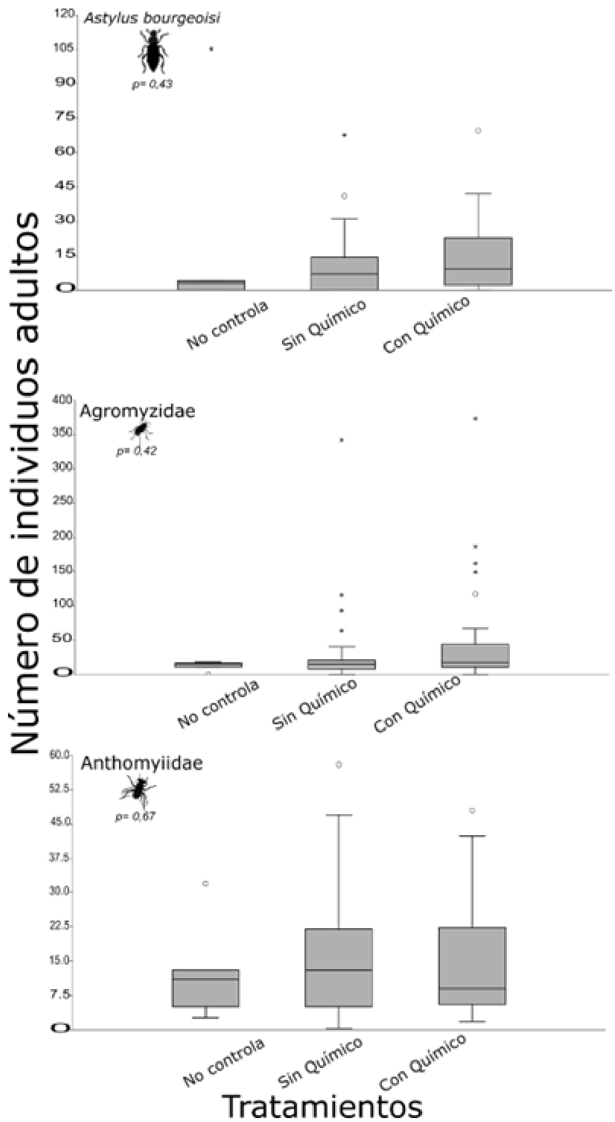

Figure 4. Effect of treatments on the abundance of pest insects monitored with sticky traps (A and C) and plate traps (B).

For pollinators, the 9 most abundant insect groups, reported as pollinators of various flowering crops, were considered. The insects analyzed included *Eristalis* sp., *Apis mellifera*, and flies from the families Stratiomyidae, Tachinidae, Sarcophagidae, Calliphoridae, Bibionidae, Syrphidae, and hymenopterans from the family Halictidae. However, all the insects sampled and uploaded to the iNaturalist app resulted in 52 different morphospecies (Inaturalist, 2022).

Some species of interest as pollinators include *Eristalis tenax* and *Eristalis bogotensis* (Syrphidae), *Cynomya cadaverina, Lucilia sericata, Calliphora vicina*, and *Chrysomya megacephala* (Calliphoridae), *Augochlorella aurata, Caenohalictus* sp., *Pseudaugochlora* sp., and *Neocorynura* sp. (Halictidae). Other identified insects included genera such as *Hedriodiscus* sp., *Netelia* sp., *Megachile* sp., *Eriothrix* sp., *Peralia* sp., and *Panzeria* sp.

The effect of the 3 treatments on the abundance of pollinators varied depending on the insect group. For insects such as *Apis mellifera, Stratiomyi-*

dae, Tachinidae, Sarcophagidae, Bibionidae, and *Syrphidae*, no statistical differences in abundances were found (ANOVA, p >0.05, Table 1). In contrast, for insects such as *Eristalis* sp., Calliphoridae, and Halictidae, lower abundances were found in chemically treated fields (ANOVA, p <0.05, Figure 5).

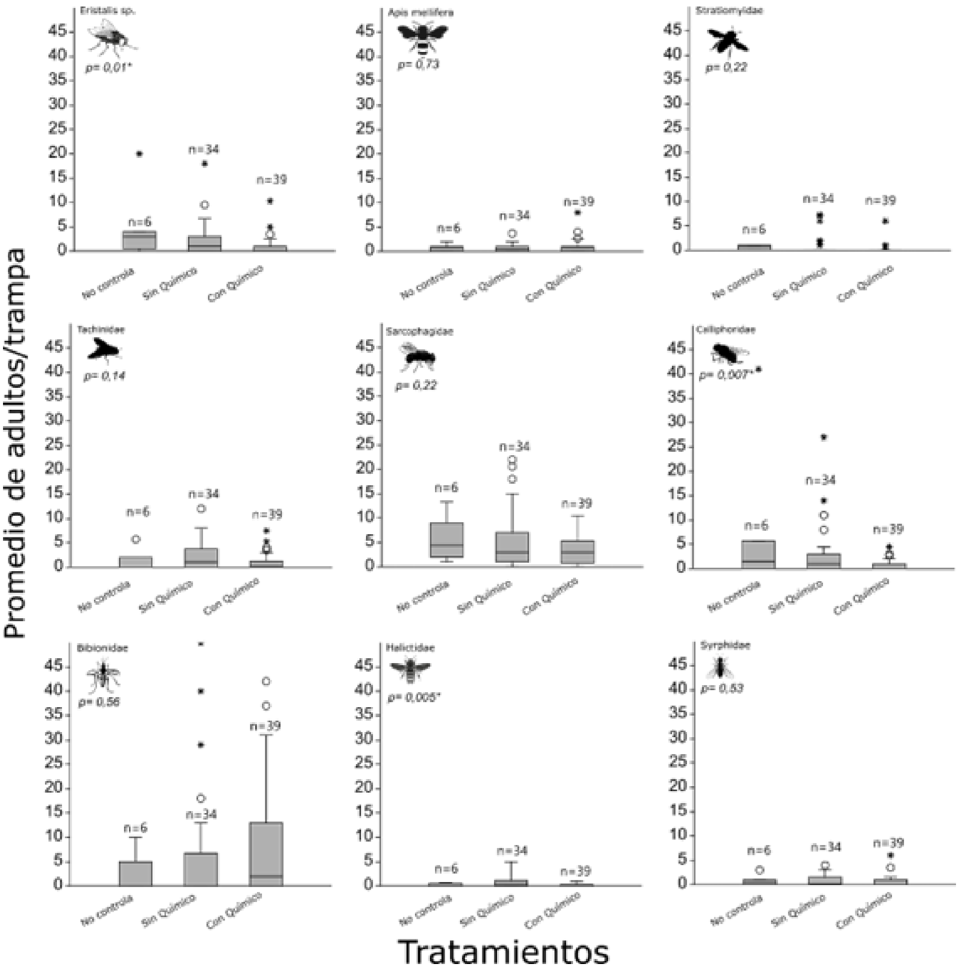

Figure 5. Effect of treatments on the abundance of beneficial insects monitored with plate traps.

Pairwise comparisons of treatments yielded the following results: i) No control vs. non-chemical was not significant (ANOVA, p <0.17), ii) No control vs. chemical was significant, with Tukey's test at 5% showing that the treatment with the lowest abundance of beneficial insects was the chemical treatment, with an average of 1.78 insects (ANOVA, p <0.002), iii) Non-chemical vs. chemical was significant, with Tukey's test at 5% showing the lowest abundance of beneficial insects in the chemical treatment (ANOVA, p <0.004).

The average height of the evaluated plants was 0.97 m, with a standard deviation of 0.24. The average number of branches was calculated to be 9.37, with a standard deviation of 2.45. Regarding the damage caused by borer pests on the main stem (measured as plant height), no significant effect of the treatments was found in the studied fields (p = 0.903; Figure 6A). On the other hand, it was observed that fields where chemical insecticides were applied had chocho plants with a greater number of branches (ANOVA, p = 0.038; Figure 6B).

Regarding estimated *chocho* productivity, where flowers and pods were counted on 10 randomly selected plants per field, significant variability was observed across the different fields, with no significant effect from any treatment (p >0.05, Figure 7). However, a positive correlation ($r = 0.19$) was found between the final yield reported by the farmers and the calculated productivity index.

3.2 Pest-Productivity Relationship

A weak positive linear relationship was calculated between the number of borers ($r^2 = 0.047$; Figure 8) and the calculated productivity index. There is a trend where a higher number of borers within the plant correlates with greater productivity. However, there is considerable variability in the results, and some plants with few borers also had productivity indices as high as plants with many borers. Figure 8 shows a slightly steeper slope after a certain pest threshold (log borers = 1.5), which may suggest that overcompensation begins after a certain level of pest attack.

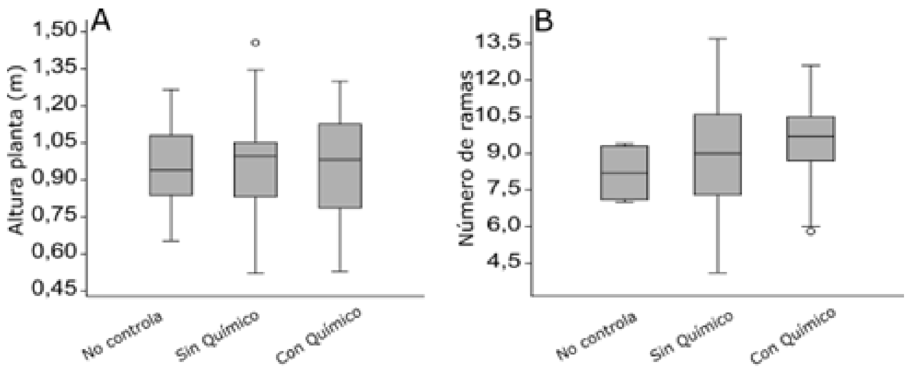

Figure 6. Relationship between treatments and borer pest damage measurements. (A) Plant height in meters, (B) Number of branches.

4 Discussion and conclusions

Several factors were not accounted for, such as soil heterogeneity, the management of surrounding crops, the residual effects of systemic insecticides, and natural habitats that could be adjacent to the study fields. On the other hand, it is noteworthy that the sample size provides a level of analysis that confirms hypotheses proposed in previous studies by the same research team. However, it is important to highlight the limitations of the experimental method, which generally analyzes a limited number of variables at a time.

Effect of Insecticides on Pest Insects

This study showed that for pest insects, no significant effects of any treatment on pest abundances were found, as noted by Struelens et al. (2021) in a previous study. This result was observed even in the treatment where the farmer did not implement any pest management actions. In other words, both the chemical and organic insecticides applied during this study were not effective in controlling the pests, with no reduction in their populations. The hypothesis is that these results could be related to two conditions: i) The active ingredients applied by the farmers were not appropriate for controlling the types of pests evaluated, and ii) The ecology of the three analyzed pests, where insecticide applications likely reached the larval stages inside the stem at sublethal doses, resulting in limited control.

In the first case, it is important to mention that 79.6% of the fields managed with chemical treatments used only three active ingredients: profenofos (acetylcholinesterase inhibitor), lambda-cyhalothrin, and cypermethrin (sodium channel modulators), all three being contact insecticides. Sixty-one percent of the fields managed in the experiment received advice from a chemical vendor or an agronomist to purchase a chemical product. As noted by Aga (2018), farmers' reliance on chemical vendors' advice is critical when it comes to controlling their pests. Zibaee Malagoli (2020) concluded that in cases of ineffective control, sublethal dose effects could exist but have yet to be evaluated for these pests. All these factors likely contribute to the development of resistance to these active ingredients.

Previous studies and surveys have demonstrated the presence of the shoot borer pest throughout much of the crop cycle (Mina et al., 2017). The hole created by the shoot borer is often used as an entry point for the other two borers found during destructive sampling. There is even evidence of trophic relationships between pests, where larvae of certain moth borers prey on larvae/pupae of the shoot borer fly.

Effect of Insecticides on Pollinators

This study indicates a negative effect of the insecticides used on the abundances of certain chocho pollinators. This effect was observed in dipterans like *Eristalis* sp., *Calliphoridae*, and hymenopterans from the *Halictidae* family, all of which are relatively large insects that contribute to the direct or indirect pollination of legumes, as noted by Miguel-Peñaloza et al. (2019). Studies like Catarino et al. (2019) have also reported varying effects depending on the pollinator and the chemical active ingredient analyzed. Another point to consider is the residual effect of systemic chemicals like neonicotinoids on pollinators (Wen et al., 2021). In the case of chocho, some farmers have opted to use such products to disinfect their seeds during planting, so considering the residuality variable would be of interest.

In the case of *Eristalis* sp. (Figure 3D; Figure 5) and other syrphid flies, adult visits to chocho flowers were observed. However, it is necessary to determine how much they contribute to the pollination of this crop, along with *Calliphoridae* and *Halictidae*. Nevertheless, the results show that fields where chemical products were used had lower pollinator abundance ($\bar{x} = 1$; SD = 1.9) compared to the control treatment ($\bar{x} = 5.1$; SD = 7.5). Syrphid flies are important pollinators with high floral visitation rates and pollen transport capabilities. In fact, *Eristalis* sp. is the most representative floral visitor among syrphid flies (Dunn et al., 2020). *Eristalis* sp. flies from May to October, which is when chocho is in bloom. They are cosmopolitan and do not always act as direct pollinators, pollinating a wide variety of plants, including legumes (Temreshev et al., 2017).

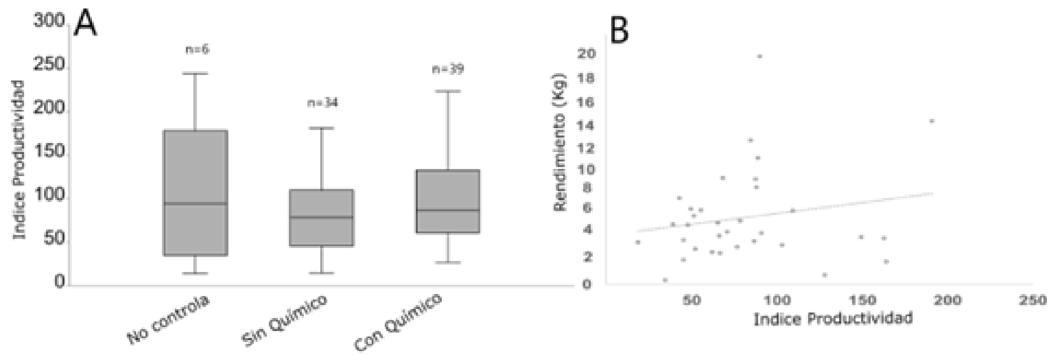

Figure 7. Relationship between treatments and yield. (A) Treatments vs. productivity index, (B) Productivity index vs. yield.

Pollinator analyses often focus exclusively on bees; however, this study highlights the role of other groups, such as these flies. Compared to bees, flies are less sensitive to habitat degradation and fragmentation, so their role as pollinators is enhanced in degraded agricultural habitats (Chakraborty et al., 2021). Studies like Garibaldi et al. (2020) have demonstrated that crop yields increase linearly with pollinator richness (number of species). In the case of *L. mutabilis*, Caligari et al. (2000) reported that there may be at least 58.8 % outcrossing, which could be harnessed by the diversity of insects visiting this crop's flowers. This diversity of insects observed during flowering necessitates the development of a methodology to confirm their effectiveness in *Lupinus* pollination.

Effect of Pesticides on Yield and Possible Overcompensation

The number of branches, recorded as a response-damage variable, was higher in fields treated with chemicals (Figure 6B). This suggests that the use of the chemicals analyzed does not directly affect the pests in question (*Anthomyiidae, Agromyzidae*, and moths). It seems that the attack of these pests predisposes the plant to a response that ultimately can positively affect yield (García and Eubanks, 2019). The average number of pods/plant was compared between healthy plants and those attacked by borers, with the latter producing 70 % more flowers than healthy plants. The hypothesis is that borer attacks do not have a decisive negative impact by limiting the growth of the central stem, as 95 % of the evaluated plants were attacked by these pests. However, herbivory by these insects causes an increase in lateral branches, a greater number of flowers and pods, which theoretically enhances productivity.

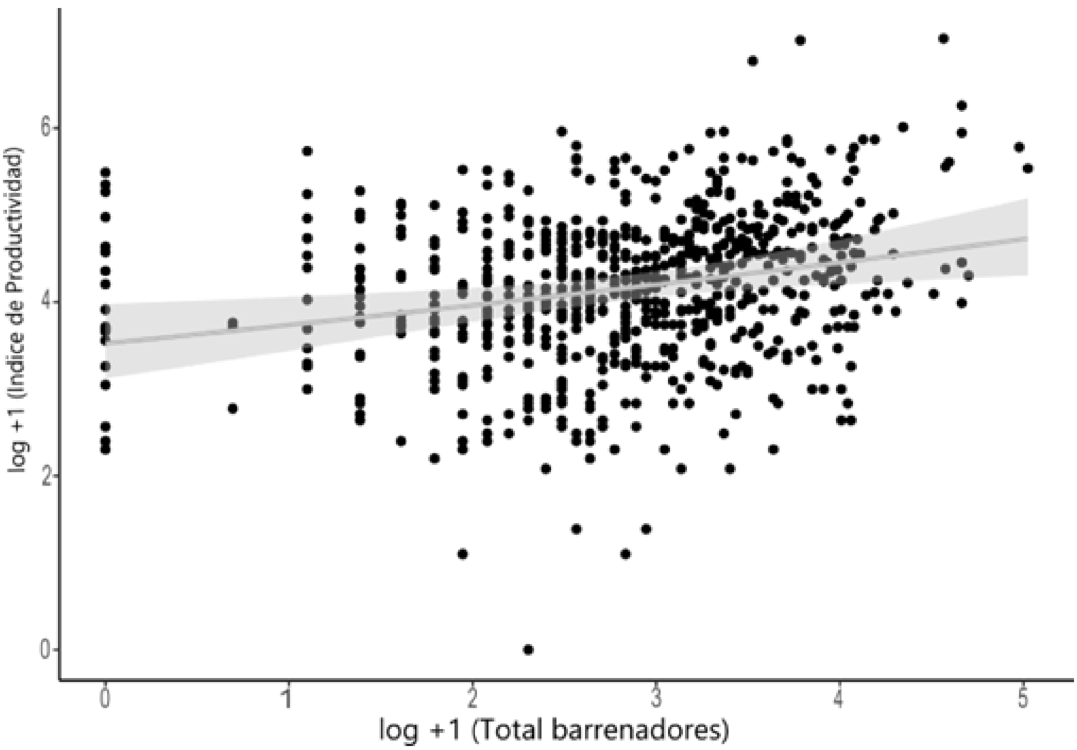

Figure 8. Relationship between the productivity index and the total number of borer pests found inside the evaluated plants (n = 770).

This possible overcompensation effect needs further analysis (in year 2 of this experiment) to understand the damage threshold, considering incidence and severity variables. Nonetheless, reports exist showing that overcompensation can double yields (comparing healthy vs. affected plants) (Poveda et al., 2018), in addition to meta-analyses providing evidence of both vegetative and reproductive overcompensation. Understanding these underlying mechanisms could be a pathway to improving integrated pest management and reducing insecticide use (García and Eubanks, 2019).

In conclusion, the interrelationships between insecticides, pests, pollinators, and crop productivity in the analyzed agroecosystem do not align as previously represented in Figure 1. The primary goal of insecticide use is to control pests (a), but as demonstrated, the most commonly recommended commercial insecticides for *chocho* cultivation do not have a clear control effect on the pests analyzed. The ecology of the main *chocho* pests, which develop by boring into stems and other plant organs, limits the effectiveness of control strategies, regardless of what they are.

It is also important to consider that insecticide application affects natural enemies (e.g., Pteromalidae microhymenopterans) found during destructive sampling. On the other hand, while pest insects are expected to negatively affect productivity (d), this can also be relative, as underlying mechanisms like overcompensation must be considered.

Regarding the relationship between insecticide use and pollinators (b), it is well known that chemicals have harmful effects on pollinators (Sánchez-Bayo and Wyckhuys, 2019). However, to better understand these effects, it is necessary to further explore pollinator-plant interactions, which are highly specialized in agricultural plants (Aguado et al., 2019), enabling a clearer understanding of the implicit ecological relationships. Regarding the insecticide-productivity relationship, as shown by Scarlato et al. (2022), pesticide use (especially insecticides) does not always have a strong relationship with crop yields.

It is crucial that results like those from this study are communicated to farmers (Wyckhuys et al., 2019). In this specific case, evidence of the poor or almost nonexistent control effects of insecticides on pests, as well as knowledge of mechanisms like overcompensation, can help reduce the use and dependence on agrochemicals. Furthermore, the social aspect and participatory research played a key role in this study, particularly in the application of treatments. In some cases, farmers did not follow the researchers' recommendations in a timely manner, and pest pressure compromised their crop health. Participatory research helps understand the variability and heterogeneity of the field, but it also poses a significant challenge, especially due to the immense variability introduced by each farmer's decisions. The year 2021 was highly atypical in terms of precipitation and temperature levels, which influenced the biology of the plants, pests, and pollinators.

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Authors' contribution

D.M.: Conceptualization, Data curation, Investigation, Methodology, Project administration, Software, Validation, Writing– original draft; J.C.: Conceptualization, Investigation, Methodology, Supervision, Validation, Writing– review editing; T.C.: Data curation, Formal analysis, Methodology, Software, Writing– review editing; I.N.: Data curation, Formal analysis, Methodology, Software, Writing– review editing; O.D.: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing– review editing.

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