

# Critical Point Analysis for Sustainable Management of *Cydia pomonella* (Lepidoptera: Tortricidae) in Smallholder Walnut Farms of Catamarca, Argentina

## Análisis de puntos críticos en la sustentabilidad del manejo de *Cydia pomonella* (Lepidoptera: Tortricidae) en pequeñas producciones nogaleras de Catamarca, Argentina

María José Cavallo<sup>1</sup>, María Cecilia Castilla<sup>1,2</sup>, Lucas Ariel Barros<sup>1,3</sup>, Oscar Eduardo Romero<sup>4</sup>, Braian Vladimír Sosa<sup>1</sup>, Martín Sebastian Espinosa<sup>5,6</sup>, Patricia Alejandra Diez<sup>1,5\*</sup>

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### ABSTRACT

In Argentina, 80% of walnut production is carried out by smallholder farms facing poor technology, production constraints, and substantial economic losses due to pests like *Cydia pomonella* (codling moth). We assessed sustainability risks linked to phytosanitary management on small farms in the Ambato region of Catamarca, Argentina. Our analysis included a “strong sustainability” framework with three key dimensions: ecological, economic, and sociocultural. A total of 26 indicators were related to this species’ management. Using semi-structured interviews, visual aids, and field surveys across seven farms, an overall sustainability index of 1.521 was calculated, with 50% of the indicators scoring below the established threshold (on a five-level sustainability scale, the selected threshold was level two). The ecological dimension emerged as the most sustainable. Limitations included absent systematic monitoring and optimisation of treatment timing, solely with agrochemical control, weak farmer-to-farmer collaboration, and insufficient training opportunities. Cluster analysis revealed four distinct groups based on phytosanitary practices. This study highlights critical intervention points and suggests agroecological strategies to enhance sustainable pest management in smallholder walnut systems.

### Keywords

codling moth • Phytosanitary management • sustainability • *Juglans regia*

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- 1 Centro Regional de Energía y Ambiente para el Desarrollo Sustentable (CONICET-UNCA). Laboratorio de Control Biológico y Biodiversidad de Insectos. C. P. 4700. Prado 366. Catamarca. Argentina.
- 2 Universidad Nacional de Tucumán. Facultad de Ciencias Naturales e Instituto Miguel Lillo. Instituto de Investigaciones de Biodiversidad Argentina. C. P. 4000. Miguel Lillo 251. Tucumán. Argentina.
- 3 Universidad Nacional de Catamarca. Facultad de Ciencias Agrarias. Cátedra Cultivos Industriales. Depto. Producción Vegetal. C. P. 4700. Av. Belgrano 300. Catamarca. Argentina.
- 4 Universidad Nacional de Catamarca. Facultad de Ciencias Agrarias. Cátedra Climatología agrícola. Depto. Clima, Suelo y Riego. Catamarca. Argentina.
- 5 Universidad Nacional de Chilecito. Departamento de Ciencias Básicas y Tecnológicas. C. P. 5360. 9 de Julio 22. Chilecito. La Rioja. Argentina. \* diezpatriciaa@gmail.com
- 6 Consejo Nacional de Investigaciones Científicas y Técnicas. C1425FQB. Godoy Cruz 2290. Buenos Aires. Argentina.



## RESUMEN

En Argentina, el 80% del sector nogalero está representado por pequeños productores, con bajo nivel tecnológico, limitaciones en la producción y presencia de especies plaga como *Cydia pomonella* ("carpocapsa"), entre otros. Se evaluaron los riesgos a la sustentabilidad del manejo fitosanitario de *C. pomonella* en minifundios de Ambato (Catamarca, Argentina), considerando tres dimensiones: ecológica, económica y sociocultural, bajo un enfoque de sustentabilidad fuerte. Se identificaron 26 indicadores relacionados con el manejo de esta especie. Mediante encuestas semiestructuradas, cartillas visuales y relevamientos en siete fincas, se determinó un Índice de sustentabilidad general de 1.521, con el 50% de los indicadores por debajo del umbral establecido (de una categorización de sustentabilidad según una escala de cinco puntos, el valor umbral seleccionado fue de dos). La dimensión ecológica fue la más destacada en términos de sustentabilidad. Las limitaciones encontradas en la práctica fitosanitaria incluyeron la falta de monitoreo de *C. pomonella* que definen momentos oportunos de control, el uso de agroquímicos como única herramienta de control, ausencia de interacción entre productores y falta de capacitaciones en fitosanidad. Mediante análisis de clúster se evidenciaron cuatro grupos según sus prácticas fitosanitarias. Se detectaron puntos críticos y propusieron herramientas para promover prácticas agroecológicas para un manejo sustentable.

### Palabras clave

carpocapsa • manejo fitosanitario • sustentabilidad • *Juglans regia*

## INTRODUCTION

Developing sustainable agriculture requires long-term flow of goods and services to meet nutritional, socio-economic, and cultural needs, within biophysical limits defined by the natural system supporting production. Sustainability encompasses multiple, interrelated objectives that demand multidisciplinary approaches (44, 50). Understanding sustainability enables evaluating and mitigating production-based environmental impacts, while accounting for market fluctuations and supply chain vulnerabilities (21). Sustainable systems must be productive, stable, resilient, and adaptable, distributing costs and benefits equitably and fostering autonomous decision-making among stakeholders (3).

Agricultural landscapes are not isolated. Production units and the environment constitute a continuous agroecosystem. Native vegetation refuges natural enemies of insect pests, supporting biodiversity. Ecological services like biotic regulation, nutrient cycling, and pollination must be managed to maintain a dynamic equilibrium between native and introduced components (32). This management depends on farmers' knowledge and decisions (49).

Walnuts (*Juglans regia* L.) represent a major agricultural sector in Argentina. Catamarca province ranks second in national walnut production, with 4063 hectares cultivated and 2619.9 tonnes annually (47). The sector comprises a range of production systems, from large-scale farms (20%) to smallholder (80%) (29, 32, 37). These last producers manage fewer than five hectares with limited technological inputs and modest yields. Challenges such as water scarcity, labour shortage, and high logistical costs hinder sustainable practices in the region. Changes in organization of the productive sector related to financing and self-management affect marketing (16).

One productivity constraint is the codling moth (*Cydia pomonella* (Linnaeus, 1758); Lepidoptera: Tortricidae), a major pest responsible for 40% to 60% yield losses (14). Larvae penetrate fruit after hatching, causing economic damage. Conventional management relies on calendar-based applications of organophosphates and pyrethroids (8), which have led to pest resistance, environmental and biodiversity degradation while risking human health (19). Alternative control strategies, including mating disruption, biopesticides, and parasitoid-based biological control, have not been widely adopted (10, 18, 25).

Transitioning towards sustainable agriculture needs robust methodologies for sustainability assessment. These assessments must be context-sensitive, cost-effective, and capable of identifying critical constraints at different spatial scales

(field, farm, region). Since sustainability is a multidimensional concept, it is summarized through indicators (43, 44). In this way, subjective and objective indicators are measured, with the latter recorded independently of what the farmer reports (*e.g.*, vegetation cover). Two main approaches characterize sustainability. Weak sustainability allows substituting natural capital with human-made capital, while strong sustainability sees both as complementary and irreplaceable (15, 21, 38, 43). This work adopted the strong sustainability perspective.

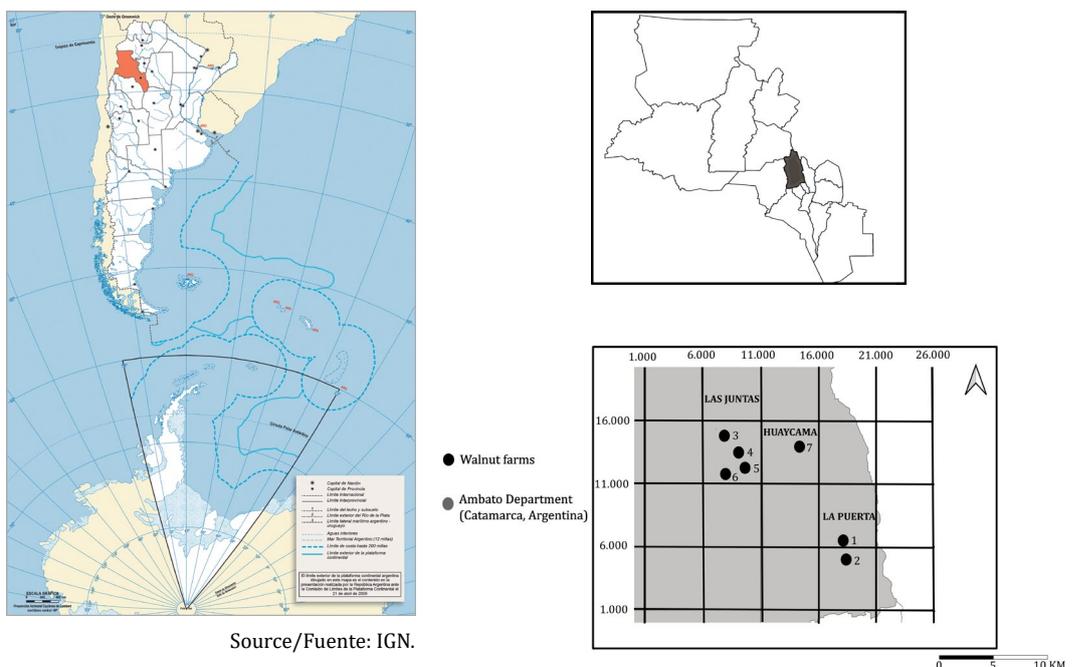
In Catamarca, previous research has addressed data on walnut varietals, types of farmers and biological aspects of *C. pomonella* (16, 32, 39, 41). To date, one study has assessed sustainability of walnut production, incorporating economic, ecological, and social dimensions within an agroecological framework (24), but no study has dealt with pest sustainable management. This study assessed the risks to sustainable phytosanitary management of *C. pomonella* by smallholder walnut farmers in Ambato (Catamarca). We employed a set of indicators and semi-structured interviews to evaluate three sustainability dimensions. (a) Ecological: Spontaneous vegetation within walnut crops supports diverse and structurally complex habitats for natural enemies of *C. pomonella*. (b) Economic: Financial losses from pest damage may exceed profits, compromising economic viability. (c) Sociocultural: Farmers largely operate in isolation and often lack knowledge about pest biology and management strategies.

This multidimensional evaluation provides insights into opportunities and constraints for sustainable pest management in smallholder agroecosystems and proposes future strategies for ecological intensification and rural resilience.

## METHODOLOGY

### Study Area

The study was conducted in the Ambato Department (28°10'14" S, 65°47'29" W) in Catamarca Province, Argentina, where seven smallholder walnut farms were selected as observational units (figure 1). Farms were chosen by considering average walnut production in the area and confirmed presence of *C. pomonella*. These farms exhibit notable varietal diversity, with predominant traditional 'Criolla' seed type and recently introduced lateral-bearing cultivars like 'Chandler'.



**Figure 1. Study area.** Walnut farms in Ambato, Catamarca, Argentina.

**Figura 1. Área de estudio.** Fincas de nogales en Ambato, Catamarca, Argentina.

### Indicator Development, Standardization, and Weighting.

Indicators were developed following Sarandón and Flores (2009). Table 1 shows eleven key variables related to phytosanitary management of *C. pomonella*, each associated with specific response indicators, yielding 26 sustainability indicators (Supplementary Material 1). Each indicator was scored on a five-point ordinal scale, ranging from 0 (least sustainable) to 4 (most sustainable), with 2 as analytical threshold. Relative weights were assigned to each indicator based on its perceived importance within the system. This weighting process was conducted through expert consensus in our research team (Supplementary Material 1).

**Table 1.** Composition of the sustainability analysis of *Cydia pomonella* management in walnut farms.

**Tabla 1.** Composición del análisis de sustentabilidad del manejo de *Cydia pomonella* en fincas de nogales.

Dimension	Variable	N° of indicators *
Ecological	A. On farm diversity management	6
	B. Spontaneous vegetation on farm edges	3
	C. Monitoring and regulation of <i>C. pomonella</i>	2
Economic	D. Economic investment in <i>C. pomonella</i> regulation	1
	E. Chemical control of <i>C. pomonella</i>	2
	F. Economic losses caused by <i>C. pomonella</i>	1
	G. Production marketing	2
Socio cultural	H. Extent of farmer knowledge on <i>C. pomonella</i> , alternative hosts and their regulation.	4
	I. Degree of knowledge of agrochemicals for the control of <i>C. pomonella</i>	1
	J. Social role of the farmer in relation to <i>C. pomonella</i> management	2
	k. Extent of farmer knowledge on ecosystem services for natural biological control of <i>C. pomonella</i>	2

\* Details of each indicator and its categorization in Supplementary Material 1.

\* Detalles de cada indicador y su categorización en Material Suplementario 1.

### Estimation of Subjective Indicators in Economic and Sociocultural Dimensions

Categorical values of subjective indicators were determined after individual semi-structured interviews with the seven walnut producers between October 2023 and June 2024. The questionnaire comprised 114 questions and was supplemented by two illustrated booklets. These visual materials assessed farmers' ability to distinguish *C. pomonella* from other insects like Lepidoptera, Diptera, and Coleoptera, including natural enemies (Supplementary Material 2).

### Estimation of Objective Indicators in the Ecological Dimension

Field-based ecological assessments were conducted on each farm. These included: (a) Vegetation characterization: number of plant species, cultivated and spontaneous, within each orchard and along field margins during autumn and spring. Species identification was conducted using field guides and images. Particular interest was given to Fabaceae, Asteraceae, and Apiaceae families, known to enhance the presence of natural enemies of *C. pomonella* (34, 35). (b) Vegetation cover was estimated using the square sampling method (33). Five points

per farm were randomly selected, corresponding to cardinal and central sectors (M1: North; M2: East; M3: South; M4: West; M5: center). At each point, 0.25 m<sup>2</sup> sampling squares were defined. Within these units, species were recorded and vegetation cover was quantified. (c) Proximity to spontaneous vegetation and habitat connectivity considered the distance from ten walnut trees per farm, randomly selected, to the nearest patch of spontaneous vegetation. Mean distance per farm was calculated.

### Data Analysis

Each farm was treated as an independent unit (20), allowing for in-depth, contextual analysis and extrapolation to the broader regional context. Five categorical sustainability levels assigned to each response identified the most influential sustainability indicators as not sustainable (0%, score 0), weak (25%, score 1), moderate (50%, score 2), optimal (75%, score 3), and strongly sustainable (100%, score 4) (1). A weighted average per indicator was calculated by combining farmer proportion providing each response with the corresponding sustainability score (1, 44). The resulting values were used to generate sustainability profiles by dimension (ecological, economic, sociocultural) for each farm, and to calculate a General Sustainability Index (GSI) for the study area. Farms scoring above the threshold value of 2 were considered optimally sustainable. Equations for indicator weighting, scoring, and index calculation are provided in Supplementary Material 1. Finally, a multivariate cluster analysis (27) grouped farms according to shared indicator profiles, eliminating variables with low discriminatory power. Correlations among farm groups identified patterns of sustainability performance.

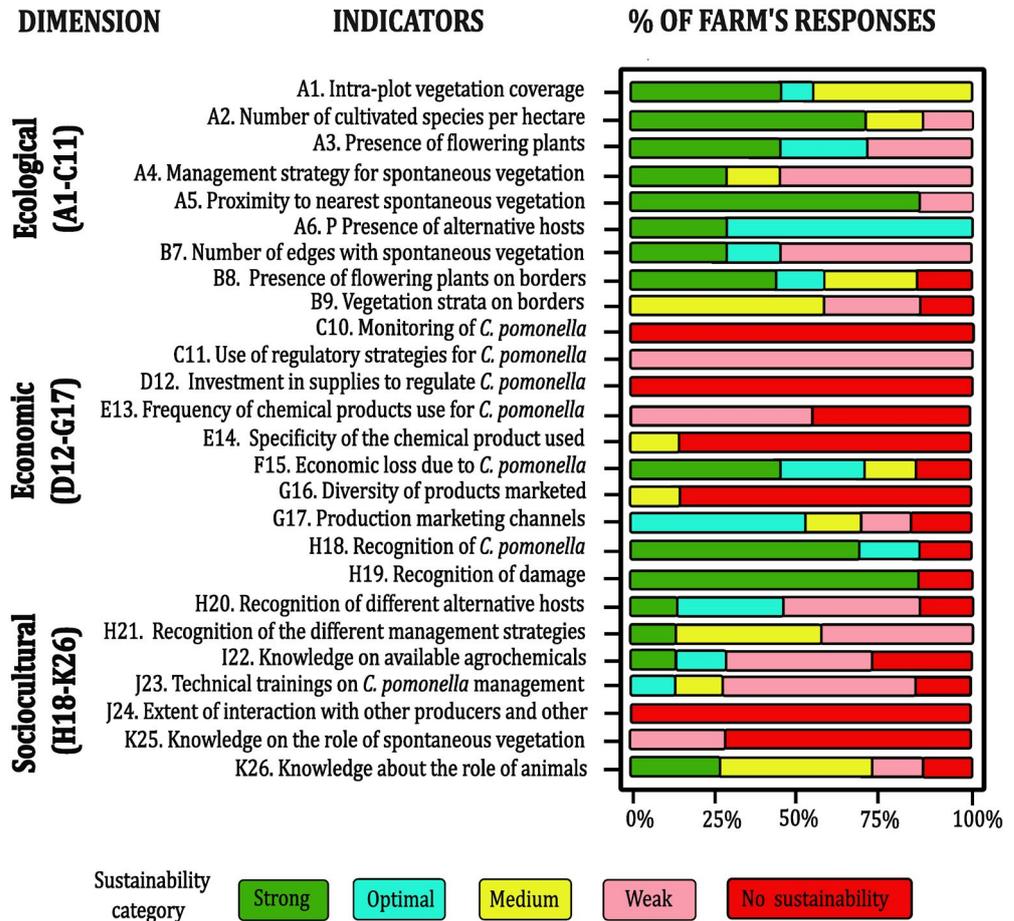
## RESULTS AND DISCUSSION

### Ecological Dimension. Indicator Variability and Biodiversity Management

Based on farmer-reported data and field measurements, ecological indicators showed the greatest variability among the three evaluated dimensions (figure 2, variables 1-11, page 6). Ecological diversity management revealed moderate to high habitat complexity (table 2, page 7). Vegetation cover across farms ranged from 45% to 95%, and mean distance to the nearest spontaneous vegetation during spring-summer was under one meter. A total of 29 plant species from 13 botanical families were identified across the farms. However, only 12 of these species belonged to families previously documented as favourable for natural enemies of *C. pomonella* (23) (table 2, page 7). Notable species included *Convolvulus arvensis* L. (bindweed), *Aloysia gratissima* G. & H. (whitebrush), *Taraxacum officinale* L. (dandelion), *Melilotus albus* M. (white sweet clover), and *Ammi visnaga* L. (toothpick plant). Notably, plant spatial and temporal distributions do not result from intentional management. Rather, they establish spontaneously, primarily along farm boundaries, which may adjoin other orchards, natural landscapes, or, in some cases, expanding urban zones.

Across farms, vegetation stratification ranged from two to four layers, suggesting a potentially favourable microhabitat structure for natural enemy communities, enhancing biological control potential. Despite this, field observations and expert communications (Engineers Romero and Barros, pers. comm.) indicate low abundance and diversity of natural enemies in the study area, including *Goniozus legneri* Gordh (Hymenoptera: Bethyridae), an effective parasitoid of several lepidopteran pests, including *C. pomonella* (5, 10, 31). Several factors may account for this discrepancy. Recent urban expansion in the Ambato Department may have influenced these results (11). This area, formerly dedicated to livestock production, has undergone changes that may have negatively affected soil quality and reduced the availability of potential refuges for natural enemies. The replacement of natural vegetation likely eliminated important sources of food and shelter for beneficial fauna, disrupting the natural landscape and ecological balance. Residual effects of *agrochemicals* accumulated over recent decades, mainly pyrethroids used for *C. pomonella* control, could also contribute to these outcomes (6). In this regard, Ferrero and collaborators (2000) demonstrated the detrimental impact of organophosphates and pyrethroids on *G. legneri*, reporting reductions in longevity, oviposition capacity, and egg-laying size. Similarly, Leyton (2023) documented the harmful effects of several

insecticides (Bifenthrin, Pirimicarb, Imidacloprid) on this parasitoid species. Without adequately monitoring pest precise emergence, chemical treatments lose effectiveness, often resulting in repeated applications. Such practices disturb ecosystem balance, reduce functional biodiversity, and compromise long-term ecological sustainability. Moreover, they may contribute to developing resistant pest populations and pose risks to human health.



**Figure 2.** Percentage distribution of indicator sustainability based on farmer responses (%). All indicators are related to *Cydia pomonella* recognition and control.

**Figura 2.** Gráfico de distribución del porcentaje de sustentabilidad de cada indicador considerando el porcentaje de respuestas de los productores. Todos los indicadores están en función de *Cydia pomonella*, su reconocimiento y control.

**Table 2.** Ecological diversity on study farms.  
**Tabla 2.** Diversidad ecológica en las fincas de estudio.

Farms	Main crop	Secondary crops	% Cob <sup>13</sup>	Dist. <sup>14</sup>	Fam. <sup>15</sup>	Div T. <sup>16</sup>	Div EN. <sup>17</sup>	Strata <sup>18</sup>
Farm 1	<i>Juglans regia</i> <sup>1</sup>	<i>Cydonia oblonga</i> <sup>2</sup> , <i>Pronus persica</i> <sup>3</sup>	52	0	6	15	4	3
Farm 2	<i>J. regia</i>	<i>C. oblonga</i> , <i>Malus domestica</i> <sup>4</sup> , <i>Pyrus sp.</i> <sup>5</sup> , <i>Prunus domestica</i> <sup>6</sup> , <i>Ficus carica</i> <sup>7</sup> . Forage ( <i>Medicago sativa</i> <sup>8</sup> )	45.6	3.5	7	12	6	2
Farm 3	<i>J. regia</i>	<i>C. oblonga</i> , <i>M. domestica</i> , <i>Pyrus</i> sp., <i>P. domestica</i> , <i>P. persica</i> , <i>Prunus dulcis</i> <sup>9</sup> . Forage ( <i>M. sativa</i> , <i>Hordeum</i> <i>vulgare</i> <sup>10</sup> )	54	2.5	11	17	5	4
Farm 4	<i>J. regia</i>	<i>C. oblonga</i> , pear, <i>P. domestica</i> . Forage ( <i>Sorghum bicolor</i> <sup>11</sup> , <i>Zea mays</i> <sup>12</sup> )	94.2	0	9	14	5	2
Farm 5	<i>J. regia</i>	<i>C. oblonga</i> , <i>M. domestica</i> , <i>Pyrus sp.</i> , <i>P. domestica</i> , <i>P. persica</i> . Forage ( <i>M. sativa</i> )	94.8	0	13	29	12	3
Farm 6	<i>J. regia</i>	<i>C. oblonga</i> , <i>M. domestica</i> , <i>P. persica</i>	96	0	9	13	2	2
Farm 7	<i>J. regia</i>	<i>C. oblonga</i> , <i>Pyrus sp.</i> , <i>P. persica</i> . Forage ( <i>M. sativa</i> , <i>Z. mays</i> ). Vegetable garden	73	0	10	16	4	3

1. Walnut. 2. Quince. 3. Peach. 4. Apple tree. 5. Pear tree. 6. Plum tree. 7. Fig tree. 8. Alfalfa. 9. Almond tree. 10. Barley. 11. Sorghum. 12. Corn. 13. Average percentage of vegetation cover on the farm. 14 Average distance from the walnut tree to the nearest spontaneous vegetation. 15. Number of families. 16. Total number of species. 17. Number of species belonging to the families Fabaceae, Asteraceae and Apiaceae: attractive to natural enemies (EN). 18. Number of vegetation strata.

1. Nogal. 2. Membrillo. 3. Durazno. 4. Manzano. 5. Peral. 6. Ciruelo. 7. Higo. 8. Alfalfa. 9. Almendro. 10. Cebada. 11. Sorgo. 12. Maíz. 13. Promedio de porcentaje de cobertura vegetal dentro de la finca. 14. Distancia promedio del nogal a la vegetación espontánea más cercana. 15. Número de familias. 16. Número de especies total. 17. Número de especies que pertenecen a las familias Fabaceae, Asteraceae y Apiaceae: atractivos para enemigos naturales (EN). 18. Cantidad de estratos.

Walnuts were the primary crop across all farms, accompanied by 11 secondary species, including fruit and forage crops (table 2). A common association was observed with *Cydonia oblonga* (quince), an alternative host for *C. pomonella*, with important implications for integrated pest management strategies. However, farmer perceptions of *C. oblonga* varied. In this study producers generally regarded quince as a low-priority crop, “not needing targeted control measures”. Some even suggested it could constitute a trap distracting *C. pomonella* away from walnut fruits. This contrasts with Rivero *et al.* (2012) from Andalgalá (Catamarca), where farmers actively managed *C. pomonella* in quince to prevent its migration into walnut orchards. These divergent approaches highlight the need for context-specific education on host dynamics and pest ecology.

The weakest ecological sustainability indicator was absent *C. pomonella* monitoring, essential for understanding population dynamics and their effects on crop yield. Yet, extensive evidence supports the critical role of pest monitoring combined with systematic data analysis, enhancing effectiveness and sustainability of integrated pest management programs (12). Farmers reported not monitoring insects or fruit damage, nor estimating number of damaged fruits per season (figure 2, indicators C10 and C11, page 6). This limits timely and effective control strategies.

#### **Economic Dimension: Sustainability Constraints in *C. pomonella* Management**

The economic analysis revealed absent monitoring as a major limit for sustainable *C. pomonella* management. No farmer reported investing in monitoring (figure 2, D12, page 6). As a result, chemical control remains predominant across most farms, applied according to calendar schedules and without rotation of active ingredients (figure 2, E13 and E14, page 6). This facilitates the emergence of resistant pest populations, already documented in fruit-producing regions like Alto Valle (Río Negro, Neuquén) (12, 48), Chile and South Africa (7, 46). The penetration of neonate *C. pomonella* larvae into fruit makes post-infestation chemical treatments ineffective. Consequently, pest control must be precisely timed. Monitoring adult population and fruit damage, managing damage thresholds, and tracking degree-day accumulation to anticipate pest emergence have proved most effective (4, 22). However, government-led phytosanitary campaigns often proceed without prior monitoring and on broad-spectrum insecticides applied at high doses, further undermining sustainability. Previous studies in the Andalgalá region have evaluated insecticide use on walnut farms and emphasized the importance of reducing environmental and worker exposure, rotating active ingredients with distinct modes of action, and incorporating at least one compound that preserves beneficial insect populations (8, 9). Despite this, some farms in Ambato report no pest control, citing costly supplies as primary barrier.

Economic losses attributed to *C. pomonella* (figure 2, F15, page 6) are approximately 20% for half of the producers, and between 20% and 50% for the second half, consistent with Andalgalá (42). Only one producer reported losses exceeding 80%. In apple production (*Malus domestica*), a 1% fruit damage threshold per hectare has been established as economic injury level (13). However, no standardized threshold exists for walnuts. Preliminary research by our group suggests a 4% fruit loss threshold, provided monitoring is conducted regularly (Diez, pers. comm.). These thresholds imply that the sustainability assessment scale used in this study should be adjusted to reflect crop-specific economic realities more accurately, enhancing control relevance.

Alternative cultural and biological strategies remain underutilized. While collecting and destroying infested fruit (*e.g.*, by burning) is recognized as a general pest control practice (36), surveyed farmers reported this approach primarily for land clearing. In addition, the use of corrugated cardboard bands to trap diapausing larvae, a low-cost method to reduce first-generation adult populations (4), is neither considered. Biological inputs, such as *C. pomonella* granulovirus (CpGV), have shown promising results among traditional growers in Pomán and Andalgalá (40), not yet in Ambato.

Additional economic indicators detected problems related to a lack of productive diversity (figure 2, G16 and G17, page 6). Most farms only sell peeled and shelled walnuts in bulk, often at very low prices. Developing value-added products, such as candied walnuts called “nueces confitadas”, walnut oil, or walnut paste, enhances farm income and economic resilience. Similar marketing innovations have been observed in other walnut-growing regions of Catamarca, including Belén and Pomán (field interviews; Poncho Festival 2024, Catamarca).

#### **Sociocultural Dimension: Insights into Knowledge and Systemic Challenges**

Interview data revealed low sociocultural sustainability risk, as most farmers demonstrated basic knowledge of *C. pomonella* biology and field behavior (figure 2, H18-H21, page 6; table 2, page 7). This knowledge is valuable, as sustainable pest control requires understanding the pest's life cycle and its interaction with the host (2). Participants identified the pest, recognized typical damage signs, and estimated seasonal presence in their orchards. However, as already mentioned, this knowledge is not consistently translated into practice (figure 2, D12, H21, K25, page 6). In this context, farmers are unwilling to invest in traps and

adopt a passive attitude, expecting the government to provide them. Moreover, they tend to only visually assess crop damage, without conducting actual counts that would evidence precise infestation levels. Additionally, producers did not recognize natural enemies in the brochure (parasitoids and predators). This result contrasts Rivero *et al.* (2012) in Catamarca, where nearly one-third of the producers recognized parasitoids on their farms.

Regarding alternative host species, only three farmers could identify all potential hosts of *C. pomonella*, and just one acknowledged the need to manage the pest in those crops (figure 2, H20, page 6). Most producers named only one or two hosts, primarily quince (*C. oblonga*), and believed that *C. pomonella* affected only walnut trees. Parallel assessments conducted on the same farms indicated that quince trees experienced an average fruit damage rate of 7% during the 2023-2024 season, with peak damage observed in January and February (Ing. Barros, pers. comm.). This gap between knowledge and reality may be linked to limited training opportunities and weak communication between farmers and agricultural institutions (figure 2, J23 and J24, page 6). Previous studies have shown that workshops facilitated by technical specialists can strengthen farmer networks and improve pest management outcomes (26, 32).

These findings only partially support our three hypotheses. Ecologically, although habitat structure may favour biological control, actual abundance and diversity of natural enemies seem insufficient. Economically, qualitative data suggest moderate to high pest impact, to be confirmed through quantitative assessments. Finally, socio-culturally, knowledge of the pest is not systematically applied in management decisions. This study diagnoses key limitations in *C. pomonella* control in Ambato, addressing a gap in the literature and laying the basis for more comprehensive, sustainable pest management in smallholder walnut systems.

### Sustainability

The average General Sustainability Index (ISg) across the evaluated farms was 1.521, under the established threshold value of 2.0. *C. pomonella* management exhibited the highest relative sustainability in the ecological dimension (1.663), followed by the sociocultural (1.571) and economic (1.329) dimensions (table 3, page 10). These findings underscore the multifaceted nature of sustainability in pest management. As expected, farms relying exclusively on chemical control did not achieve the highest sustainability scores. In several cases, farms without control practices demonstrated comparable or even higher sustainability indices. This counterintuitive outcome can be attributed to absent monitoring practices across farms, regardless of management intensity. Control measurements without monitoring, particularly chemical applications, are often untimely, excessive, ineffective and economic-ecologically expensive. The absence of integrated monitoring systems constitutes a critical barrier for sustainable pest control.

### Cluster Analysis

Cluster analysis based on the General Sustainability Index (ISg) identified four distinct groups of farms reflecting sustainability degrees (table 3, page 10). Cluster One with the highest sustainability level, comprised only Farm 2, with an ISg of 2.509, surpassing the threshold of 2.0. However, closer examination revealed that this value was driven by higher economic and sociocultural scores, while ecological performance remained limited. The producer demonstrated knowledge of *C. pomonella* management, including alternative hosts and appropriate agrochemical use. Ecological indicators on this farm revealed sparse vegetation cover, greater distances to spontaneous vegetation, and limited floral diversity from ecologically relevant plant families. At the opposite end, Cluster Two was represented by Farm 5, with the lowest sustainability score (ISg: 0.887). Unlike the other units, this farm's primary activity is livestock production, with walnut cultivation playing a minor role. Consequently, *C. pomonella* was not perceived as a significant threat, and no management strategies were implemented. Between these extremes, cluster Three included Farms 4, 6, and 7 (ISg: 1.331, 1.233, and 1.335, respectively), and Cluster Four included Farms 1 and 3 (ISg: 1.654 and 1.698, respectively). These clusters differed primarily in their ecological characteristics. Farms in Cluster Four exhibited higher vegetation cover and greater plant diversity, including flowering species and fruit crops, supporting beneficial arthropod communities. These farmers also reported greater economic losses due to *C. pomonella*, indicating pest pressure and greater economic dependency on walnut production.

**Table 3.** Indicator values in seven walnut farms in Ambato, Argentina, and general sustainability conditions.**Tabla 3.** Valores de los indicadores empleados en siete fincas de Nogales, Ambato, Argentina y condiciones de sustentabilidad general.

Farms <sup>1</sup>	Variables											Sustainability values <sup>2</sup>			
	A	B	C	D	E	F	G	H	I	J	K	DE	DK	DSC	ISg
<b>Farm 1</b>	2.00	1.40	1.00	0.00	0.67	8.00	0.50	5.67	6.00	1.00	1.33	1.10	1.53	2.33	1.65
<b>Farm 2</b>	2.56	1.00	4.00	2.00	3.33	8.00	2.50	8.00	8.00	0.67	1.33	1.89	2.64	3.00	2.51
<b>Farm 3</b>	3.33	2.60	1.00	0.00	0.00	8.00	1.50	6.33	2.00	0.33	2.00	1.73	1.59	1.78	1.69
<b>Farm 4</b>	3.56	2.20	1.00	0.00	0.67	4.00	1.50	5.33	2.00	0.00	0.33	1.69	1.03	1.28	1.33
<b>Farm 5</b>	4.00	3.20	1.00	0.00	0.00	0.00	0.00	1.33	2.00	0.33	0.00	2.05	0.00	0.61	0.89
<b>Farm 6</b>	2.56	1.80	1.00	0.00	0.67	6.00	1.50	5.00	0.00	0.33	0.67	1.34	1.36	1.00	1.23
<b>Farm 7</b>	3.56	2.80	1.00	0.00	0.00	6.00	1.00	5.00	0.00	0.33	0.67	1.84	1.17	1.00	1.34
<b>Overall average area</b>	<b>3.08</b>	<b>2.14</b>	<b>1.43</b>	<b>0.29</b>	<b>0.76</b>	<b>5.71</b>	<b>1.21</b>	<b>5.24</b>	<b>2.86</b>	<b>0.43</b>	<b>0.91</b>	<b>1.66</b>	<b>1.33</b>	<b>1.57</b>	<b>1.52</b>

1. Walnut farms. A. On-farm diversity management. B. Spontaneous vegetation on farm edges. C. Monitoring and regulation of *C. pomonella*. D. Economic investment in *C. pomonella* regulation. E. Chemical control of *C. pomonella*. F. Economic losses caused by *C. pomonella*. G. Production marketing. H. Extent of farmer knowledge on *C. pomonella*, alternative hosts and their regulation. I. Degree of knowledge of agrochemicals for the control of *C. pomonella*. J. Social role of the farmer concerning *C. pomonella* management. k. Extent of farmer knowledge on ecosystem services for natural biological control of *C. pomonella*. 2. Results are averages of the indicators constituting each variable. DE=Ecological Dimension. DK: Economic Dimension. DSC: Socio-Cultural Dimension. ISg: General Sustainability Index. Formula. Supplementary material 1.

1. Fincas de nogales. A. Manejo de la diversidad en la finca. B. Vegetación espontánea en los bordes de la finca. C. Monitoreo y regulación de *C. pomonella*. D. Inversión económica en la regulación de *C. pomonella*. E. Control químico de *C. pomonella*. F. Pérdidas económicas causadas por *C. pomonella*. G. Comercialización de la producción. H. Grado de conocimiento de los agricultores sobre *C. pomonella*, hospedantes alternativos y su regulación. I. Grado de conocimiento de los agroquímicos para el control de *C. pomonella*. J. Rol social del agricultor en relación con el manejo de *C. pomonella*. k. Grado de conocimiento de los agricultores sobre los servicios ecosistémicos para el control biológico natural de *C. pomonella*. 2. Los resultados son el promedio de los indicadores que conforman la variable. DE=Dimensión Ecológica. DK: Dimensión económica. DSC: Dimensión Sociocultural. ISg: Índice de Sustentabilidad General. Fórmula. Material suplementario 1.

## CONCLUSION

This study represents the first assessment of sustainability gaps in the phytosanitary management of *C. pomonella* among smallholder walnut farmers in Argentina. The findings highlight that effective and sustainable pest control must encompass ecological, economic, and sociocultural dimensions, rather than single-point interventions. To initiate meaningful changes, participatory frameworks must engage all relevant stakeholders, including farmers, academic researchers, and public institutions involved in agricultural policy and extension services. These workshops should be collaborative spaces for knowledge exchange, trust-building, and context-appropriate co-design management strategies. Key prevention must implement systematic pest monitoring and promote ecological practices aimed at regenerating native vegetation and enhancing habitats for natural enemies. Such efforts would strengthen ecosystem resilience and support reestablishing natural biological control mechanisms for *C. pomonella*. In parallel, enhancing market strategies through value-added products (e.g., processed walnuts, specialty foods) could improve profitability, promote investment in sustainable practices, and increase resilience of walnut production systems. Ultimately, sustainability in smallholder agricultural systems depends on technical improvements in pest control and integration of holistic strategies that align ecological integrity with economic viability and social inclusion. Without adequate profitability, the relative importance of ecological and social factors diminishes, weakening long-term sustainability. Addressing vulnerabilities across all sustainability dimensions (not just one) is essential for effective management of *C. pomonella* and secure regional walnut production.

## SUPPLEMENTARY MATERIAL

[https://docs.google.com/document/d/1fVJGbaYYPVGXzDZbZkx76EqjtAr0z1yB/edit?usp=drive\\_link&ouid=111310786017351827239&rtpof=true&sd=true](https://docs.google.com/document/d/1fVJGbaYYPVGXzDZbZkx76EqjtAr0z1yB/edit?usp=drive_link&ouid=111310786017351827239&rtpof=true&sd=true)

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