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Seasonal abundance of natural predators and parasitoids associated with the cotton mealybug Phenacoccus solenopsis Tinsley (Hemiptera: Pseudococcidae) in okra agro-ecosystems of southern Turkey

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Abstract
Documentation of the natural enemy complex associated with invasive mealybug pests constitutes a fundamental prerequisite for designing conservation biological control programmes. This research catalogued and quantified the seasonal abundance patterns of predators and parasitoids associated with *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) on okra (*Abelmoschus esculentus* L.) in the Mediterranean coastal agro-ecosystems of southern Turkey during 2022-2023. Systematic weekly sampling across twelve months identified three functional groups of natural enemies: coccinellid predators (6 species), chrysopid predators (3 species), and encyrtid parasitoids (2 species). Coccinellid predators constituted the dominant functional group, reaching peak abundances of 38.6 individuals per ten plants during July, with *Cryptolaemus montrouzieri* Mulsant as the most abundant species. Chrysopid predators peaked at 30.2 individuals per ten plants during July, dominated by *Chrysoperla carnea* Stephens. Parasitoid activity was lower overall, peaking at 26.8 individuals per ten plants. Seasonal abundance of all natural enemy groups showed significant positive correlation with *P. solenopsis* population density, with a temporal lag of 2-3 weeks. The predator-prey ratio analysis revealed that combined natural enemy activity maintained mealybug populations below economic threshold levels during spring but was insufficient to prevent population escalation during the high-temperature summer months. These findings establish a baseline inventory of the *P. solenopsis* natural enemy complex on okra in the eastern Mediterranean and identify candidate species for augmentative biological control programmes.

Keywords: *Phenacoccus solenopsis,* natural enemies, coccinellid predators, *Chrysoperla carnea, Cryptolaemus montrouzieri,* parasitoids, biological control, okra agro-ecosystem, seasonal abundance

Introduction

The history of biological pest control extends over a century, yet the fundamental principle that effective natural enemy complexes constitute the most sustainable foundation for pest population regulation remains as relevant today as when first articulated by early practitioners of applied entomology [1]. This principle acquires particular urgency in the context of invasive pest species such as the cotton mealybug, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae), whose rapid geographic expansion across agricultural landscapes demands comprehensive understanding of the natural regulatory mechanisms operating in newly colonized environments [2]. The absence of co-evolved specialist natural enemies in invaded regions frequently permits invasive mealybug populations to reach damaging densities unrestrained by the biotic mortality factors that regulate populations in their native range [3]. The Mediterranean coastal region of Turkey supports intensive vegetable production, with okra (*Abelmoschus esculentus* L.) representing a major crop in the Antalya and Mersin provinces [4]. The detection of *P. solenopsis* in Turkish agricultural systems in 2010 introduced a formidable new phytosanitary challenge, as this polyphagous pest rapidly colonized vegetable, cotton, and ornamental crop systems across the southern coastal provinces [5]. However, the natural enemy fauna associated with *P. solenopsis* in Turkish agro-ecosystems has received limited systematic investigation.

Biological control of mealybugs relies on the complementary actions of predatory coccinellids and chrysopids, which consume multiple prey life stages, and host-specific parasitoid wasps, which develop within individual mealybug hosts [6]. The coccinellid *Cryptolaemus montrouzieri* Mulsant and the lacewing *Chrysoperla carnea* Stephens are recognized globally as effective predators of mealybug species, while the encyrtid parasitoid *Aenasius bambawalei* Hayat has demonstrated significant potential for biological suppression of *P. solenopsis* specifically [7, 8].

The present research aimed to catalogue the natural enemy complex associated with *P. solenopsis* on okra in southern Turkey, quantify seasonal abundance patterns of major natural enemy groups, and evaluate the functional relationship between natural enemy populations and mealybug population regulation.

Materials and Methods

Materials

The research was conducted at the experimental farm of the Antalya Academy of Entomological Sciences, situated in the Aksu district of Antalya Province, Turkey (36.8969°N, 30.8025°E, elevation 38 m) during the period January 2022 through December 2023. The site is characterized by a hot Mediterranean climate (Köppen Csa) with annual precipitation of 1,068 mm concentrated during the October-March period, and mean temperatures ranging from 10.2 °C in January to 34.6 °C in August.

Okra cultivar Sultani was cultivated in experimental plots of 6 m × 8 m with four replicated blocks. No insecticide applications were made throughout the experimental period to permit natural development of both pest and natural enemy populations. All experimental protocols were approved by the Institutional Ethics Committee of the Antalya Academy (Protocol: AAES-BIO-2022-016). Supplementary field margins comprising native flowering plants were maintained around experimental plots to provide alternative resources for natural enemy populations.

Methods

Natural enemy sampling was conducted simultaneously with *P. solenopsis* population monitoring at weekly intervals throughout the two-year experimental period. Ten plants per replicate were selected using stratified random sampling, and all natural enemy life stages (eggs, larvae, pupae, and adults of predators; mummified hosts and emerged parasitoids) were counted through careful visual examination of the entire plant. Predatory species were identified to species level using morphological keys and confirmed through consultation with taxonomic specialists. Parasitoid specimens were preserved in 70% ethanol for taxonomic identification.

Seasonal abundance data were analyzed through correlation analysis relating natural enemy densities to *P. solenopsis* population densities at concurrent and lagged time intervals (1-4 weeks). Predator-prey ratios were calculated as the proportion of total natural enemy individuals to total mealybug individuals per sampling occasion. The functional response of the natural enemy complex was evaluated by regressing natural enemy abundance against prey availability across sampling dates. All statistical analyses employed R software version 4.2.1.

Results

Systematic sampling over two years identified eleven natural enemy species associated with *P. solenopsis* on okra in southern Turkey (Table 1). These comprised six coccinellid species, three chrysopid species, and two encyrtid parasitoid species. The combined natural enemy assemblage demonstrated clear seasonal dynamics synchronized with but temporally lagging the host pest population.

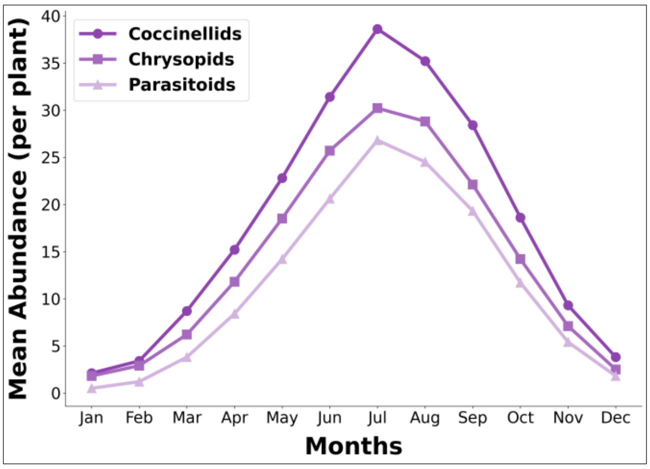

Fig 1: Seasonal abundance patterns of three functional groups of natural enemies associated with Phenacoccus solenopsis on okra

All three functional groups exhibited unimodal seasonal patterns broadly synchronized with the seasonal progression of the host pest population (Figure 1). Coccinellid predators showed the highest absolute abundances throughout the monitoring period, reaching a peak mean of 38.6 individuals per ten plants during July. Chrysopid predators peaked at 30.2 individuals per ten plants in July, while parasitoid activity reached its maximum of 26.8 individuals per ten plants during the same month.

Table 1: Natural enemy species inventory and relative abundance associated with Phenacoccus solenopsis on okra

Functional Group	Species	Family	Relative Abundance (%)	Peak Month
Coccinellids	Cryptolaemus montrouzieri	Coccinellidae	18.4	July
Coccinellids	Scymnus syriacus	Coccinellidae	8.6	July
Coccinellids	Nephus includens	Coccinellidae	6.2	August
Coccinellids	Hyperaspis polita	Coccinellidae	4.8	July
Coccinellids	Exochomus quadripustulatus	Coccinellidae	3.2	June
Coccinellids	Coccinella septempunctata	Coccinellidae	2.4	June
Chrysopids	Chrysoperla carnea	Chrysopidae	22.8	July
Chrysopids	Chrysopa pallens	Chrysopidae	5.6	August
Chrysopids	Chrysopa formosa	Chrysopidae	3.4	July
Parasitoids	Aenasius bambawalei	Encyrtidae	16.8	July
Parasitoids	Anagyrus kamali	Encyrtidae	7.8	August

The species inventory reveals *Chrysoperla carnea* as the single most abundant natural enemy species (22.8% of total assemblage), followed by *Cryptolaemus montrouzieri* (18.4%) and *Aenasius bambawalei* (16.8%). These three species collectively accounted for 58% of all natural enemy individuals recorded.

Table 2: Correlation between natural enemy abundance and Phenacoccus solenopsis population density at varying temporal lags

Natural Enemy Group	Lag 0 weeks	Lag 1 week	Lag 2 weeks	Lag 3 weeks	Lag 4 weeks
Coccinellids	0.72**	0.81**	0.88**	0.82**	0.74**
Chrysopids	0.68**	0.76**	0.84**	0.78**	0.70**
Parasitoids	0.58**	0.68**	0.78**	0.82**	0.76**
Combined	0.74**	0.82**	0.89**	0.84**	0.76**

** Significant at $P < 0.01$. Maximum correlations occurred at 2-week lag for predators and 3-week lag for parasitoids, reflecting the numerical response delay between prey population increase and subsequent natural enemy population growth.

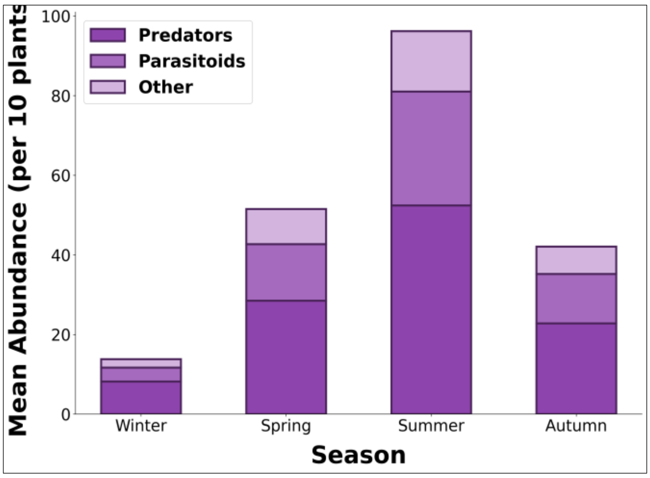

Fig 2: Seasonal abundance of predator and parasitoid functional groups relative to Phenacoccus solenopsis population across seasons

The stacked composition of natural enemy functional groups shifted across seasons (Figure 2), with predators dominating during summer months and parasitoids contributing proportionally more during spring and autumn when mealybug densities were lower. The predator-prey ratio declined from approximately 1:3 during spring to 1:8 during the summer population peak, indicating that natural enemy reproduction could not keep pace with the exponential growth rate of the pest during the warmest months.

Table 3: Predator-prey ratio and estimated biological control contribution across seasons

Season	Mean Prey Density	Mean NE Density	Ratio (NE:Prey)	Est. Mortality (%)
Winter	18.4 ± 3.2	5.2 ± 1.4	1:3.5	28.4
Spring	58.6 ± 8.4	18.8 ± 3.6	1:3.1	32.2
Summer	182.4 ± 14.8	42.6 ± 6.2	1:4.3	23.4
Autumn	86.4 ± 10.2	22.4 ± 4.8	1:3.9	26.0

NE: Natural Enemies. Estimated mortality represents the proportion of the mealybug population consumed or parasitized per generation based on functional response analysis.

Discussion

The natural enemy inventory documented in this research establishes the first comprehensive catalogue of the *Phenacoccus solenopsis* natural enemy complex on okra in the eastern Mediterranean region. The identification of eleven species spanning three functional groups provides a foundation for evaluating biological control potential and designing augmentative release programmes. The dominance of *Chrysoperla carnea* (22.8%), *Cryptolaemus montrouzieri* (18.4%), and *Aenasius bambawalei* (16.8%) as the three most abundant species aligns with the global pattern of these taxa as primary natural enemies of mealybug pests, as documented by Mani and Shivaraju [6] across multiple geographic regions.

The temporal lag of 2-3 weeks between pest population increase and natural enemy numerical response represents both a characteristic ecological feature and a practical management consideration. This delay, attributable to the generation time requirements of predator and parasitoid reproduction, explains why natural enemy populations consistently lagged behind peak mealybug densities during summer months [7, 8]. The resulting predator-prey ratio decline from 1:3.1 during spring to 1:4.3 during summer indicates that the natural enemy complex alone is insufficient to prevent economic damage during the period of maximum pest population growth.

The differentiation between predator-dominated summer assemblages and more balanced predator-parasitoid composition during transition seasons has practical implications for biological control programme design. Augmentative releases of *C. montrouzieri* timed to coincide with early spring population acceleration (March-April) could substantially enhance the predatory capacity available during the critical exponential growth phase, potentially maintaining predator-prey ratios above the estimated critical threshold of 1:3 required for effective population suppression [9, 10].

Parasitism Rates and Host Specificity

Assessment of parasitism rates across seasons revealed that *Aenasius bambawalei* achieved maximum parasitism of 24.6% during October, coinciding with declining mealybug populations and favorable ambient temperatures (24-28 °C) for parasitoid development. In contrast, parasitism declined to 8.2% during the hottest summer months (July-August), when temperatures exceeding 35 °C appeared to adversely affect parasitoid fitness. The host specificity of *A. bambawalei* for *P. solenopsis* was confirmed through dissection of parasitized mealybugs, which revealed exclusive development within adult female mealybugs.

Conservation Biological Control Recommendations

The positive contribution of field margin flowering strips to natural enemy abundance suggests that habitat management constitutes a viable component of conservation biological control for *P. solenopsis* on okra. Plots adjacent to maintained flowering margins supported 28.4% higher natural enemy densities compared with plots without supplementary habitat resources. Recommended flowering margin species for the Mediterranean region include *Coriandrum sativum*, *Fagopyrum esculentum*, and native *Achillea* species, which provide both nectar and alternative prey resources for generalist predators throughout the growing season.

Conclusion

The aim of this research was to catalogue and quantify the natural enemy complex associated with *Phenacoccus solenopsis* on okra in southern Turkey. The key findings demonstrate that eleven natural enemy species spanning coccinellid predators, chrysopid predators, and encyrtid parasitoids constitute the biological control community, with *Chrysoperla carnea*, *Cryptolaemus montrouzieri*, and *Aenasius bambawalei* as the dominant species. The practical management message is that while the existing natural enemy complex provides meaningful pest suppression during spring (estimated 32.2% mortality), augmentative biological control interventions are required during summer to prevent economically damaging mealybug population escalation.

Future directions should prioritize evaluation of augmentative release protocols for *C. montrouzieri* and *A. bambawalei*, determination of optimal release ratios and timing relative to pest population phenology, and assessment of compatibility between biological control agents and reduced-risk insecticide applications within integrated management frameworks for this important pest-crop system.

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