CALIFORNIA'S MEDITERRANEAN FRUIT FLY ERADICATION PROGRAM:

IMPACT OF RISING TEMPERATURES ON

POPULATION DYNAMICS AND CONTROL EFFORTS

by

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GLOSSARY and ABBREVIATIONS

- AIC: Akaike Information Criterion; a model selection tool where lower values indicate better fit based on model accuracy and simplicity (Allotey & Owusu, 2025a).
- AW-IFFM: Area-Wide Integrated Fruit Fly Management; a regional strategy using SIT, trapping, and sanitation (USDA, 2023).
- BIO6: A Medfly allele linked to cold tolerance, possibly aiding winter survival in cooler areas (Deschepper et al., 2024).
- Broader biocontrol definition: CDFA, IPPC, and IAEA define SIT as a form of biological control, recognizing sterile insects as targeted and environmentally safe tools (IPPC, 2014; IAEA, 2025, CDFA, 2025).
- CDFA: California Department of Food and Agriculture.
- Classical biological control: Use of predators, parasitoids, or pathogens form a pest's native range for long-term suppression (NIFA, 2024).
- CLIMEX: Bioclimatic software predicting species distribution based on climate (Syniszewska et al., 2024; Wernicke et al., 2024).
- Delimitation: Defining infestation boundaries to guide eradication efforts (CDFA, 2024).
- Eradication vs. Suppression: Eradication eliminates pests entirely; suppression lowers populations below damaging levels (Carey, 1992; CDFA, 2025).
- IAEA: International Atomic Energy Agency; promotes SIT as a safe biocontrol method (IAEA, 2025).
- IPPC: International Plant Protection Convention; recognizes sterile insects as biocontrol agents (IPPC, 2014).
- Malathion: A broad-spectrum organophosphate insecticide formerly used in aerial Medfly eradication (USDA & CDFA, 2008).
- MED-FOES: Mediterranean Fruit Fly Forecasting Outbreak and Eradication Simulation; a model guiding Medfly control in California (CDFA & USDA, 2008).
- MOSCAMED: U.S.-Mexico-Guatemala program to stop Medfly spread from Central America.
- NCEI: National Center for Environmental Information.
- NOAA: National Oceanic and Atmospheric Administration.
- NIFA: National Institute of Food and Agriculture; defines classical biological control as using natural enemies like predators, parasitoids, or pathogens for pest suppression (NIFA, 2024).
- Overwintering: The ability of a species to survive winter in a dormant or slowed state, resuming activity when conditions improve (Liquido et al., 1994).

GLOSSARY and ABBREVIATIONS CONTINUED

- PRP: Preventive Release Program; a suppression strategy in southern California involving continuous sterile male releases to prevent establishment.
- SIT: Sterile Insect Technique; a control method where sterile males are released to mate with wild females, preventing viable offspring (CDFA, 2025).
- Spinosad: A low-toxicity insecticide from soil bacteria used in bait sprays (CDFA, 2024).
- Sterile-to-wild fly ratio: A SIT performance metric measuring sterile males relative to wild ones in traps (Carey et al., 2017).
- Thermal refuge: A warm microenvironment, often urban, that supports Medfly survival in winter (Wernicke et al., 2024; Syniszewska et al., 2024).
- UHI: Urban Heat Islands.
- USDA: United States Department of Agriculture.

ABSTRACT

The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), is a globally significant pest with a broad host range and high ecological adaptability. It infests over 250 crop types and causes significant economic losses through crop damage and trade restrictions, resulting in persistent pressure on California's high-value agricultural economy and reinforcing the need for long-term management. In California, eradication efforts rely on the Sterile Insect Technique (SIT) and the Preventive Release Program (PRP), but rising temperatures linked to climate change threaten their long-term success. Therefore, I investigated how rising temperatures affect Medfly population dynamics, their thermal resilience, and the effectiveness of eradication strategies in California. I analyzed 37 years (1987–2024) of detection and temperature data across 13 counties, using regional averages and models stratified by biologically meaningful temperature ranges to assess how temperature influences fly activity and control outcomes. Daily Medfly trap records from the California Department of Food and Agriculture (CDFA) and daily surface temperature data from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) were aggregated to monthly values to ensure temporal consistency across datasets and support long-term trend analysis. Wild Medfly counts were highest below 24°C (75.2°F) and declined sharply above 29°C (84.2°F), indicating temperature-linked suppression. SIT success also declined in warmer conditions, especially in southern California, where sterile-to-wild fly ratios dropped below performance thresholds. Regional warming trends, confirmed through annual and five-year moving averages, further contextualize these declines. Continued detections in cooler counties such as Alameda and Santa Clara suggest localized adaptation or microclimatic buffering. My findings highlight the need for regionally tailored, climate-adjusted strategies to address ecological variability and constraints of current pest management methods.

INTRODUCTION

The Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), commonly known as the Medfly, is one of the most destructive agricultural pests in the world. Its broad host range, rapid reproductive cycle, and adaptability to diverse climates threaten California's $50 billion fruit and vegetable industries, with potential losses exceeding $1 billion per year due to crop damage and trade restrictions (Carey, 1992; CDFA, 2024). To prevent the permanent establishment of wild Medfly populations, California's Department of Food and Agriculture (CDFA) relies on the Preventive Release Program's (PRP) Sterile Insect Technique (SIT), a biological control strategy involving the mass release of sterile males (CDFA & APHIS/USDA, 2008). While classical biological control typically involves releasing natural enemies such as predators or parasitoids, CDFA adopts the broader definition used by the International Plant Protection Convention (IPPC) and International Atomic Energy Agency (IAEA), which recognize sterile insects as beneficial biological control agents (IPPC, 2014; IAEA, 2025; CDFA, 2025). However, climate change, with rising temperatures and shifting seasonal patterns, raises concerns about the long-term effectiveness of SIT and other eradication strategies, as their performance under evolving environmental conditions is not fully understood (Johnson & USDA, 2023; Gilioli et al., 2021). I address the impact of climate-driven temperature changes on Medfly eradication efforts in California to inform climate-resilient pest management strategies. Limited empirical evidence on how climate change affects eradication outcomes necessitates targeted research to develop adaptive approaches.

BACKGROUND

Medfly Biology

Medflies belong to the Tephritidae family, with *C. capitata* being one of the most economically damaging species due to its impact on more than 250 crops (CDFA, 2024; Liquido et al., 1991). Adult Medflies typically are about 5 mm long (Figure 1). They have a dark thorax with silver-white markings, a banded yellow-brown abdomen, and patterned wings that help them blend into their environments, especially against light-filtered fruit and foliage (Gazit, 2015). This cryptic coloration protects them from predators (Gazit, 2015).

Figure 1. Adult Medfly on a leaf (PSB, 2023).

Female Medflies damage host fruit using their ovipositor to puncture the skin and lay eggs just beneath the surface (CDFA, 2024; USDA, 2023; Figure 2). A single female can deposit as many as 10 eggs in one oviposition event and may lay between 300 and 800 eggs throughout their lifetime (Carey, 1992). These oviposition "stings" create entry points for pathogens and trigger tissue degradation as the hatched larvae feed on the fruit's interior (Liquido et al., 1991).

The maggots consume the fruit pulp which then accelerates the decay and often causes the fruit to soften and drop to the ground prematurely (USDA, 2023). After developing inside the fruit, mature larvae exit and burrow into the soil to pupate, typically at depths of 1 to 5 cm. This pupation depth protects them from predators and environmental extremes, enabling the cycle of infestation to continue (Wernicke et al., 2024; Gilioli et al., 2021).

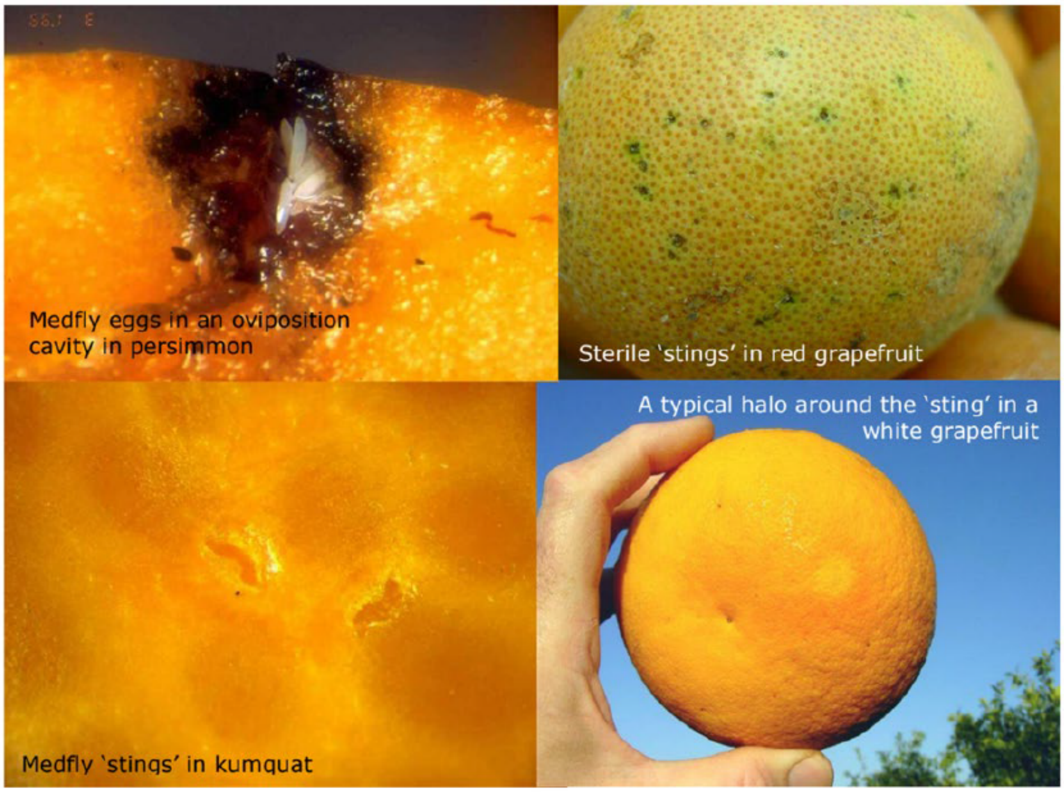

Figure 2. Medfly oviposition damage in fruit (Gazit, 2015).

Once they emerge from their pupal stage, adult Medflies seek out sugary foods to meet their energy requirements and obtain protein for reproduction. Their diet primarily consists of nectar, honeydew, decaying fruit, and microbial deposits on plant surfaces (Gazit, 2015; USDA, 2023). Males form small groups known as leks, releasing pheromones to attract females, while females may mate multiple times, enhancing genetic diversity (Gazit, 2015; Carey, 2010). Under optimal conditions, typically between 24°C (75.2°F) and 29°C (84.2°F), Medflies can complete their life cycle in 18 to 33 days, producing as many as 10 to 15 overlapping generations each year (Deschepper et al., 2024; Jaiswal et al., 2023; Syniszewska et al., 2024). Wild Medflies often outlive lab-reared ones, with females surviving over 140 days in captivity, likely due to early-life environmental conditioning that enhances resilience (Carey, 2010). In comparative studies, female Medflies from Mediterranean climates, such as those in Greece and Portugal, lived significantly longer than those from tropical regions, such as Guatemala and Kenya, likely due to selection for surviving seasonal scarcity (Carey, 2010). This difference impacts SIT efficacy, as tropical sterile males from facilities in Hawaii and Guatemala may be less competitive in California's variable climate (Carey, 2010; Johnson & USDA, 2023; Carey et al., 2017). These biological traits demonstrate the need for regionally adapted eradication strategies.

Medfly Behavioral Ecology

The ecological success of the Medfly is largely due to its generalist host range, reproductive flexibility, and ability to thrive in diverse agricultural and urban landscapes (CDFA, 2025; Liquido et al., 1991). Unlike more specialized pests, such as the olive or cherry fruit fly, the Medfly can infest more than 250 fruit and vegetable crops, exploiting even suboptimal hosts like lemons when preferred peaches are unavailable (Carey, 2010; CDFA, 2025). Individual Medflies are relatively sedentary, dispersing only a few hundred meters naturally, but human activities, such as transport of infested fruits or packing materials, facilitate long-distance movement (Dominiak & Taylor-Hukins, 2022; CDFA & APHIS, 2008). These passive dispersal methods make containment challenging, leading to unpredictable introductions far from known infestation zones (Carey et al., 2017).

Once established, Medflies can reproduce year-round in warmer climates, exploiting unmonitored food sources such as backyard trees, ornamental plants, and abandoned orchards, particularly in urban and peri-urban areas (CDFA, 2025; Johnson & USDA, 2023). They also display behavioral adaptability and signs of physiological and genetic adjustments in response to environmental stressors. Recent genetic studies have identified cold-tolerant alleles, such as BIO6, in Medfly populations from northern California, Europe, and Argentina, indicating potential adaptation to cooler climates (Deschepper et al., 2024). This adaptability may allow seasonal temperature declines to no longer restrict population growth, especially in cooler regions previously considered low risk (Syniszewska et al., 2024; Carey et al., 2017).

While Medflies do not directly disrupt natural ecosystems, their impact on agriculture is severe, causing crop losses, expensive eradication campaigns, and trade disruptions, especially for California's more high-value fruit exports (Carey, 1992; CDFA, 2024). Even minor outbreaks can trigger strict quarantines, increasing regulatory costs and damaging the commercial reputation of affected areas (CDFAA, 2025; Carey & UC Davis, 2024). The fly's advanced traits, combined with global trade and climate variability, enable its long-distance spread and local survival, making it one of the most challenging agricultural pests to manage (Gilioli et al., 2021; Johnson & USDA, 2023; Syniszewska et al., 2024).

Global Eradication Efforts

Efforts to eradicate the Medfly have been ongoing for over a century, evolving to include chemical, biological, and regulatory strategies tailored to regional climates, crop diversity, policies, and Medfly population genetics (CDFA & APHIS, 2008; Wernicke et al., 2024). Chemical methods, such as aerial insecticide application, were historically crucial for suppressing outbreaks (Dreistadt & Dahlsten, 1986; Carey, 2010). Over time, biological controls, including the Sterile Insect Technique (SIT), parasitoid wasps, and cultural controls, have become central to integrated pest management programs (Suarez et al., 2023; CDFA & APHIS, 2008). Agencies also use border control protocols, dense trapping networks, and trade regulations to prevent introductions and contain outbreaks (Dominiak & Taylor-Hukins, 2022; Johnson & USDA, 2023).

One of the earliest documented eradication efforts occurred in Hawaii, where the Medfly was first detected in 1910 (CDFA & APHIS, 2008). Initial control relied on insecticides, but Hawaii shifted to long-term SIT suppression (Carey, 2010; Johnson & USDA, 2023). In SIT, mass-reared sterile male flies are irradiated and released to mate with wild females, producing no viable offspring and reducing population levels (Johnson & USDA, 2023). SIT is a cornerstone of global Medfly programs, supported by quarantine enforcement, trap networks, and cultural controls like fruit stripping (Dominiak & Taylor-Hukins, 2022; Suarez et al., 2023). However, SIT's effectiveness depends on sterile male viability and competitiveness, which can be compromised by temperature stress or environmental mismatch, highlighting the need for locally adapted protocols (Carey et al., 2017; Syniszewska et al., 2024).

The Mediterranean Fruit Fly Forecasting Outbreak and Eradication Simulation program (MOSCAMED), launched in 1975, spans Guatemala, Mexico, and parts of the southern United States, combining SIT with surveillance and trade regulations to create a “biological barrier” against northward Medfly spread (CDFA & APHIS, 2008). In Argentina, the Area-Wide Integrated Fruit Fly Management (AW-IFFM) integrates SIT with parasitoid wasps and targeted spraying, leveraging multiple control agents to address diverse cropping systems (Suarez et al., 2023). Despite these achievements, eradication outcomes vary widely across geographic and climatic contexts. For instance, annual Medfly detections in Austria and northern Italy rarely survive winter, except in urban areas, suggesting reintroductions rather than persistence (Wernicke et al., 2024). Whereas in warmer climates with milder winters, Medflies can persist over multiple generations, which further complicates eradication (Gilioli et al., 2021). Mediterranean biotypes tend to have longer lifespans and higher survival during scarcity, unlike shorter-lived, more cold-sensitive tropical strains (Carey, 2010). Global programs also face policy challenges, as premature "eradication" declarations may obscure persistent or reintroduced populations, delaying adaptive management (Carey, 2010). These lessons emphasize the importance of climate-informed, regionally tailored strategies, as explored in this study's California context.

California Eradication Efforts

The Medfly was first detected in California in 1975. Since then, the state has been actively working to prevent the establishment of permanent populations (CDFA, 2025; Carey, 1992; Carey et al., 2017). Initially, eradication strategies focused on manually removing fruit from trees and the aerial spraying of malathion pesticides over homes and urban neighborhoods. Then, by the 1980s, these aggressive tactics faced widespread public opposition and led to the adoption of less invasive methods in the following years (Dreistadt & Dahlsten, 1986; Carey, 2010; Carey et al., 2017).

There was a turning point in 1980 when a wild Medfly was detected in northern Santa Clara County on the same day that wild flies were found in the southern Los Angeles Basin. This event showed that the Medfly threat had become statewide and triggered a two-year eradication program in the north, an area previously considered inhospitable to the fly due to its cooler climate (Carey, 1987). Over time, continued outbreaks and pressure from southern hotspots led to the creation of the Preventive Release Program (PRP), which shifted the focus from reactive to proactive control strategies. The program operates only in southern counties such as Los Angeles, Riverside, Orange, and San Bernardino (Figure 3) and uses sterile insect releases to suppress wild populations. The state's PRP serves as California's main control method, where sterile male Medflies are released by plane to mate with wild females, producing no viable offspring (Johnson & USDA, 2023). Approximately 200 million sterile males are released each month through the PRP (CDFA, 2025; CDFA, Plant Health Division, PDEP, 2025).

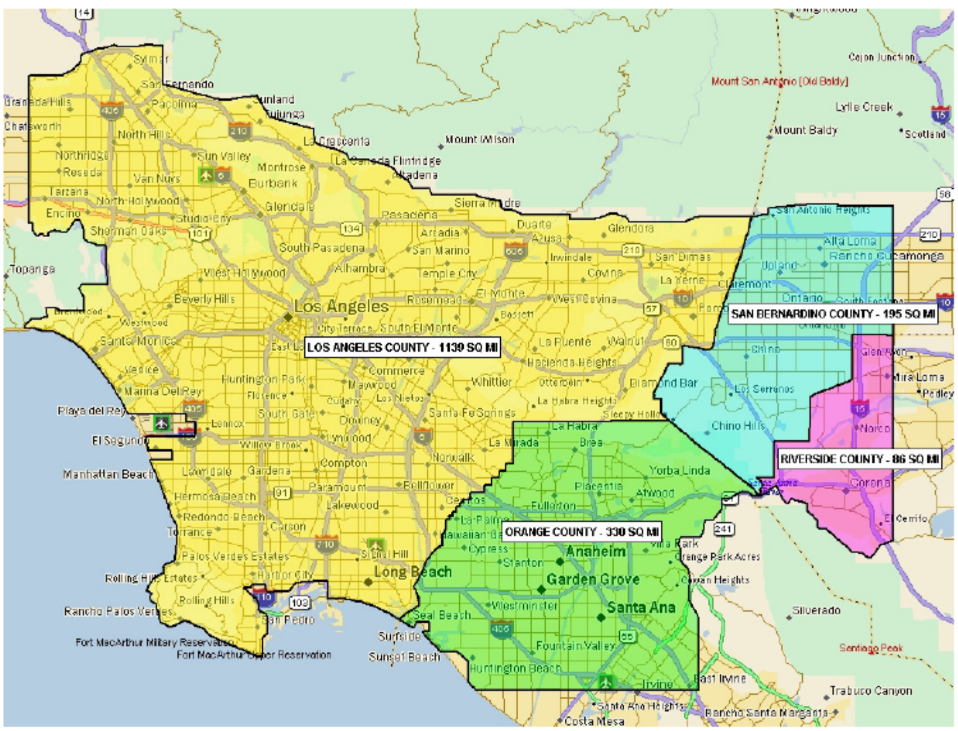

Figure 3. Medfly PRP Zones in Southern California (CDFA, 2025).

California declares eradication when no wild Medflies are detected for three full generations, which typically takes 60 to 90 days depending on temperature (CDFA, 2024; Carey et al., 2017). However, this strategy has been criticized for potentially overlooking hidden or slow-growing populations, especially in urban areas with backyard fruit trees that are not regularly monitored or trapped (Carey, 2010; Carey & UC Davis, 2024). Detection of at least two wild flies is required to trigger state and county eradication and delimitation protocols (CDFA, 2024). These efforts include ground treatments using Spinosad bait sprays, which combine an insecticide with extremely low non-target toxicity and an attractant to draw in adult flies. When adult flies feed on the bait, Spinosad disrupts their nervous system, leading to death. Because the spray is applied to foliage rather than directly to fruit, it reduces exposure risks for people, pets, and beneficial insects. It has minimal acute toxicity to vertebrates, making it a relatively safe option for ground treatments. Additional control measures include removing fruit within a 100-to-200 m radius of the detection site and placing intensive traps to define the infested area (CDFA, 2024; CDFA & APHIS, 2008). Although outbreaks continue to occur, these systems are designed to respond quickly and contain the pest before it spreads farther (CDFA, 2025; USDA, 2023).

Eradication in the Context of Climate Change

Climate change increasingly complicates Medfly control and eradication globally (Skendzic et al., 2021; Gilioli et al., 2021). The species is highly sensitive to temperature, with an optimal reproductive range of 24°C (75.2°F) to 29°C (84.2°F), where it can complete its life cycle in 18 to 33 days (Deschepper et al., 2024; Jaiswal et al., 2023; Syniszewska et al., 2024). Warmer temperatures may intensify population pressure by shortening generation time, although the extent to which climate shifts alter Medfly persistence across diverse regions remains uncertain (Strobl et al., 2024; Gilioli et al., 2021).

Rising temperatures could enable Medfly populations to overwinter in regions previously too cold, potentially expanding their range, but field evidence on this shift is limited (Rao et al., 2024; Carey et al., 2017; Liquido et al., 1994). Temperature changes also pose challenges for SIT, as heat stress during development, storage, or transport may reduce sterile male lifespan and mating competitiveness (Carey, 2010; Johnson & USDA, 2023; Carey et al., 2017). Microclimatic factors, such as urban heat islands (UHI) and irrigated landscapes, may sustain Medfly populations in otherwise unsuitable conditions, yet their role in control outcomes is not well documented (Wernicke et al., 2024; Syniszewska et al., 2024). These uncertainties highlight the need for climate-informed eradication strategies, although specific knowledge gaps, such as those related to fine-scale environmental drivers and thermal tolerance, require further exploration (Allotey & Owusu, 2025a, 2025b; Carey et al., 2017).

Climate-driven Uncertainties in Medfly Eradication

Despite decades of eradication efforts, climate change introduces significant uncertainties regarding the Medfly's distribution, persistence, and control, limiting the effectiveness of current strategies (Gilioli et al., 2021; Syniszewska et al., 2014, 2020, 2024). A major knowledge gap concerns how localized climatic variability, such as coastal fog belts, UHIs, and irrigated microclimates, influences Medfly population dynamics and eradication outcomes across diverse California regions (Johnson & USDA, 2023; Wernicke et al., 2024). Although higher temperatures are known to accelerate development and shorten generation time (Jaiswal et al., 2023; Strobl et al., 2024), the role of fine-scale thermal conditions enabling year-round persistence (particularly in contrasting northern and southern climates) is poorly understood (Carey et al., 2017; Syniszewska et al., 2014, 2020, 2024).

Another critical uncertainty involves the potential thermal tolerance of wild Medfly populations, with evidence of cold-tolerant alleles (BIO6) in cooler regions like northern California, Europe, and Argentina suggesting possible survival in previously unsuitable environments, yet field studies documenting such resilience are limited (Deschepper et al., 2024; Carey, 2010). Also, the extent to which the Sterile Insect Technique (SIT) is affected by warmer or variable field conditions remains unclear, as sterile males from controlled facilities may face challenges in mating success and survival under fluctuating temperatures, but empirical data are limited (Carey, 2010; Carey et al., 2017).

Current forecasting tools, such as CLIMEX and MED-FOES, rely on coarse-scale climatic data and often fail to account for fine-scale ecological factors like irrigation, soil temperature, UHIs, and backyard host trees, which create spatially heterogeneous conditions in suburban and semi-urban areas (Syniszewska et al., 2024; Gilioli et al., 2021). These factors may sustain Medfly populations in otherwise unsuitable conditions, complicating monitoring efforts outside routine agricultural surveillance (Wernicke et al., 2024; Johnson & USDA, 2023). Addressing these gaps requires empirical research to clarify how microclimatic variability, thermal tolerance, and modeling limitations impact Medfly persistence and control, informing climate-responsive, spatially targeted management strategies (Carey et al., 2017; CDFA, 2025; Syniszewska et al., 2024).

RESEARCH QUESTION

The central question I address is how rising temperatures influence Medfly population dynamics, their thermal resilience, and the effectiveness of eradication strategies in California. As climate change continues to challenge the reliability of traditional control methods, such as

SIT, I identify temperature-driven patterns that can support the development of more climate-responsive and regionally adapted approaches to pest management under future environmental conditions.

Objectives

The first objective is to determine how wild Medfly populations and seasonal activity respond to three biologically relevant temperature categories: below 24°C (75.2°F), between 24–29°C (75.2–84.2°F), and above 29°C (84.2°F). These surface temperature thresholds correspond to physiological limits that influence Medfly reproduction and survival: cooler temperatures may inhibit development, moderate temperatures support optimal reproduction, and extreme heat can impair fertility and reduce lifespan (Deschepper et al., 2024; Jaiswal et al., 2023). Identifying how wild fly counts vary across these temperature ranges can inform climate-responsive surveillance by pinpointing the most likely periods and locations for outbreaks, allowing for more targeted trap placement and rapid response efforts when population increases are most likely.

The second objective is to assess how elevated temperatures (above 29°C/84.2°F) affect the sterile-to-wild fly ratio, a metric that indicates the effectiveness of sterile fly releases (Carey et al., 2017). If elevated temperatures are associated with lower ratios, this could suggest reduced SIT performance during periods of higher temperature, guiding potential modifications to release schedules or developing more heat-tolerant strains.

The third objective is to evaluate whether regional differences in persistence between southern and northern California suggest adaptation among wild populations due to temperature changes. The aim is to tailor eradication strategies by region, especially in counties where

Medfly populations appear resilient to adverse weather patterns and where warming trends may enable year-round survival. While southern California already operates a more region-specific program through the Preventative Release Program (PRP), a comparable level of targeted management has not yet been established for the north.

METHODS

To evaluate the influence of temperature on Medfly dynamics and SIT efficacy, I used 37 years (1987-2024) of daily Medfly detection records from the California Department of Food and Agriculture (CDFA), which were aggregated to monthly values to account for missing or inconsistent daily entries across counties. Corresponding daily surface air temperature data, representing ambient air conditions recorded at ground level, were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) and aggregated to monthly values to ensure consistency across records and account for data gaps. Thirteen counties were grouped into northern (Alameda, Marin, San Mateo, Santa Clara, Solano) and southern (Imperial, Los Angeles, Orange, Riverside, San Bernardino, San Diego, Tulare, Ventura) regions. Monthly Medfly and temperature data were then matched by county and year to support temporal consistency in the analysis.

Temperature values were grouped into three categories reflecting Medfly physiological thresholds: below 24°C/75.2°F, between 24–29°C/75.2–84.2°F, and above 29°C/84.2°F. These categories were used as explanatory variables to model population dynamics and sterile-to-wild fly ratios. Regional temperature trends were also analyzed using both annual averages and 5-year moving averages to capture long-term warming trends. These trends are referenced in figures throughout the Results section to contextualize regional warming patterns.

Due to the ecological nature of the data, which included frequent zeros and substantial variation across space and time, generalized linear models were employed. Poisson, Negative Binomial, Zero-Inflated, and Hurdle models were tested, with model selection based on Akaike Information Criterion (AIC) values. Negative Binomial models were preferred for wild Medfly counts and regional persistence due to their superior handling of overdispersion compared to Poisson or Zero-inflated models, as evidenced by lower AIC values. Mixed-effects models included random intercepts for county and year to control for spatial and temporal autocorrelation. A linear mixed-effects model was used for sterile-to-wild fly ratios, with inferences on threshold comparisons due to the complexity of ratio data (Allotey & Owusu, 2025a). Model diagnostics were performed using the DHARMa package to evaluate fit and zero-inflation. Final model structures were developed with consulting support by Allotey and Owusu (2025a, 2025b). Final models used Negative Binomial distributions for wild Medfly counts and regional persistence analysis, while a linear mixed-effects model was used to examine the sterile-to-wild fly ratio.

Data Limitations

Several limitations were acknowledged in this study. Inconsistencies in trap type, placement, and maintenance over time and across counties may have affected the comparability of detection records. Temperature reporting methods also varied, with some counties providing maximum/minimum values and others reporting at fixed observation times. To minimize bias, temperature values were standardized, and all data were aggregated to the monthly level. Counties or months with fewer than ten detection records were excluded to reduce the influence of sparsely populated samples.

Wild Medfly detections exhibited strong overdispersion and frequent zero counts, necessitating the use of specialized model structures such as Negative Binomial and zero-inflated models. While mixed-effects modeling helped mitigate some of the structural challenges, model performance was still affected by low data density in certain northern counties, especially at temperatures above 29°C (84.2°F). The lack of metadata on trap calibration, land use, humidity, or irrigation made it difficult to control for additional environmental variables that may affect Medfly behavior. These limitations highlight the need for improved data collection protocols in future monitoring programs, including the integration of high-resolution climate and land cover variables. Sensitivity analyses confirmed that temperature-related suppression patterns were robust to data subsetting, increasing confidence in the study's core findings despite these challenges.

RESULTS

Wild Medfly counts and SIT performance varied significantly with temperature, region, and year across California. Table 1 summarizes the model outputs, including regression coefficients (β), standard errors (SE), p-values, and 95% confidence intervals (CIs). Confidence intervals were calculated as $\beta \pm 1.96 \times SE$. The results are organized according to the study's three research objectives: wild fly activity across temperature thresholds, SIT performance under elevated temperatures, and regional differences in persistence.

Table 1. Summary of modeled effects of temperature and region on wild medfly counts and Sterile Insect Technique (SIT) effectiveness (1987–2024).

Objective	**Effect**	**β (Coefficient)**	**SE**	**p-value**	**95% CI**	**Model Type**	**Figure(s)**
1	Year (Time Effect)	-0.4809	0.1759	0.006	(-0.825, -0.137)	Mixed-Effects Negative Binomial	Figure 4

1	Temp >29°C(84.2°F) vs. <24°C(75.2°F)	-1.4335	0.8503	0.092	(-3.100, 0.233)	Mixed-Effects Negative Binomial	Figure 4
1	Temp 24-29°C (75.2 – 84.2°F) vs. <24°C (75.2°F)	-0.5163	0.5771	0.371	(-1.647, 0.615)	Mixed-Effects Negative Binomial	Figure 4
1	Spearman's ρ (Temp vs. Wild Count)	-0.037	--	0.009	--	Correlation (Exploratory Analysis)	Figure 4
2	SIT Ratio <10:1 Above 29°C (84.2°F) (Southern only)	--	--	<0.05*	--	Linear Mixed-Effects (Inferred)	Figure 6
3	Southern vs. Northern Region	1.3509	0.3139	<0.0001	(0.736, 1.966)	Fixed-Effects Negative Binomial	Figure 8
3	Temp >29°C (84.2°F) vs. <29°C (84.2°F) (Regional Model)	-2.7976	0.7714	0.0003	(-4.310, -1.285)	Fixed-Effects Negative Binomial	Figure 8
3	Temp 24-29°C (75.2 – 84.2°F) vs. <24°C (75.2°F) (Regional Model)	-1.3323	0.5958	0.025	(-2.500, -0.165)	Fixed-Effects Negative Binomial	Figure 8

* p-value for SIT ratio below the 10:1 threshold above 29°C is based on an inference from a linear mixed-effects model (Allotey and Owusu, 2025a, 2025b) and does not include a full coefficient or standard error estimate due to the use of threshold-based comparisons for ratio data.

Objective 1: Wild Medfly Activity Across Temperature Thresholds

Wild Medfly populations declined significantly from 1987 to 2024, with the highest predicted counts occurring under cooler conditions below 24°C (75.2°F). Fly activity was strongest at these lower temperatures, moderately reduced between 24–29°C (75.2–84.2°F), and lowest above 29°C (84.2°F) (Figure 4).

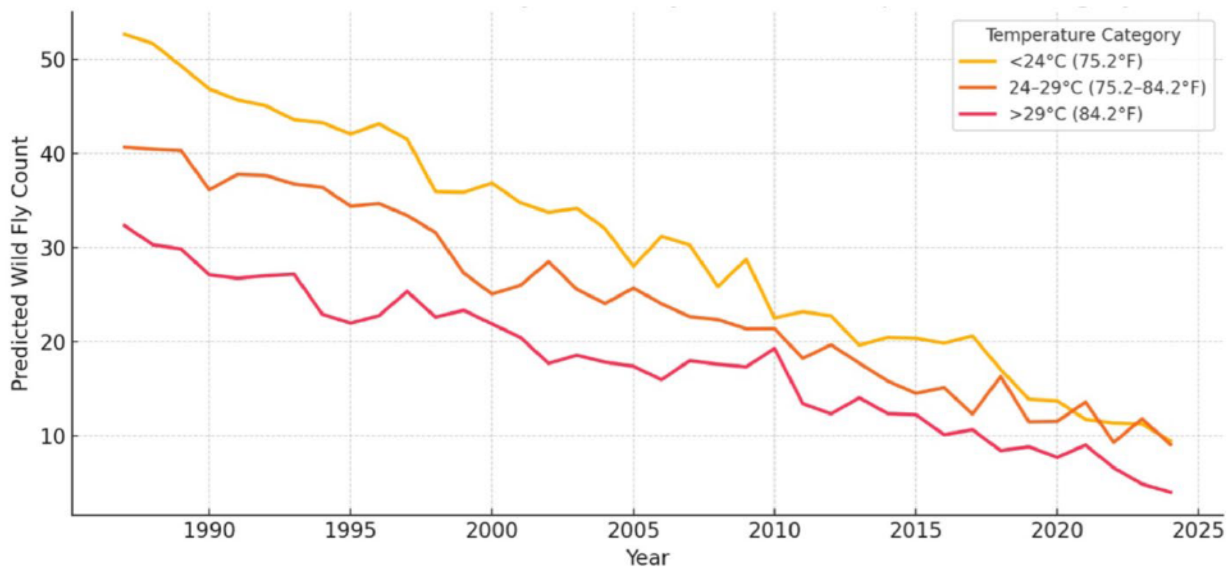

Figure 4. Predicted Wild Medfly Counts by Year and Temperature Category.
Model-based predictions show a long-term decline in wild Medfly counts from 1987 to 2024 across all temperature categories: below 24°C (75.2°F), between 24–29°C (75.2–84.2°F), and above 29°C (84.2°F). The highest predicted counts occurred under cooler conditions, with substantial suppression observed as temperatures increased.

Predicted mean counts declined from 12.5 flies per trap under cooler conditions, to 7.3 flies per trap in the intermediate range, and 2.1 flies per trap at the highest temperatures. This temperature-linked suppression was further supported by a weak but statistically significant negative correlation between temperature and wild Medfly count (Spearman's $\rho = -0.037$, $p = 0.009$; Table 1). However, the weak correlation suggests that other unmeasured factors, such as humidity, irrigation, or land use, likely play a larger role in driving Medfly population dynamics. Predicted wild fly counts declined across all temperature categories over time (Figure 4). The steepest declines correspond to years with higher temperatures, suggesting cumulative warming effects on Medfly reproduction.

Figure 5 supports this context, showing that annual temperatures steadily increased between 1987 and 2024, particularly in southern California.

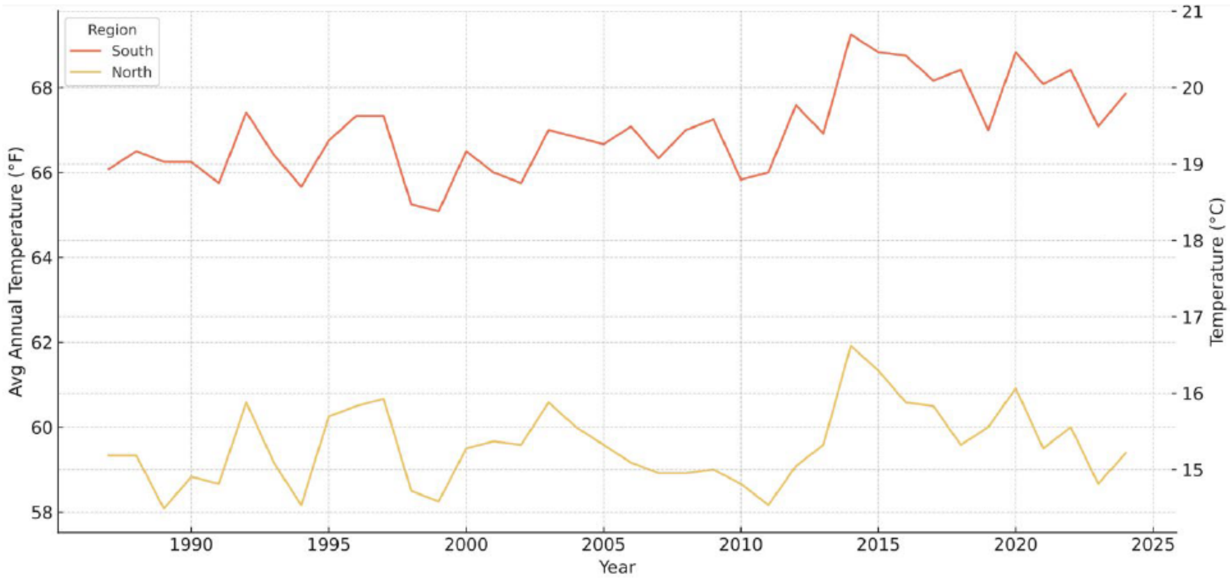

Figure 5. Annual Temperature Trendlines by Region (Jan 1987 – Jan 2024, Smoothed 2024). Average annual temperatures from 1987 to 2024 are shown for northern and southern California. A smoothed value for 2024 (mean of 2021–2023) was applied to minimize distortion from partial-year data. Southern California consistently shows higher temperatures and a more pronounced warming trend.

These trends align with the model results from Table 1, which include a strong negative year effect ($\beta = -0.4809$, $p = 0.006$) and a negative coefficient for temperatures above 29°C (84.2°F) ($\beta = -1.4335$, $p = 0.092$), indicating a decreasing trend in fly counts, although this effect was not statistically significant. Collectively, these findings suggest that rising temperatures have increasingly constrained Medfly activity during historically productive summer months.

Objective 2: Effects of Higher Temperatures on SIT Effectiveness

Sterile-to-wild fly ratios declined sharply above 29°C (84.2°F) in southern California, falling below the standard 10:1 SIT effectiveness threshold. Figure 6 illustrates these trends, with median ratios dropping to approximately 6.2 in the warmest temperature category compared to 15.3 at temperatures below 24°C (75.2°F).

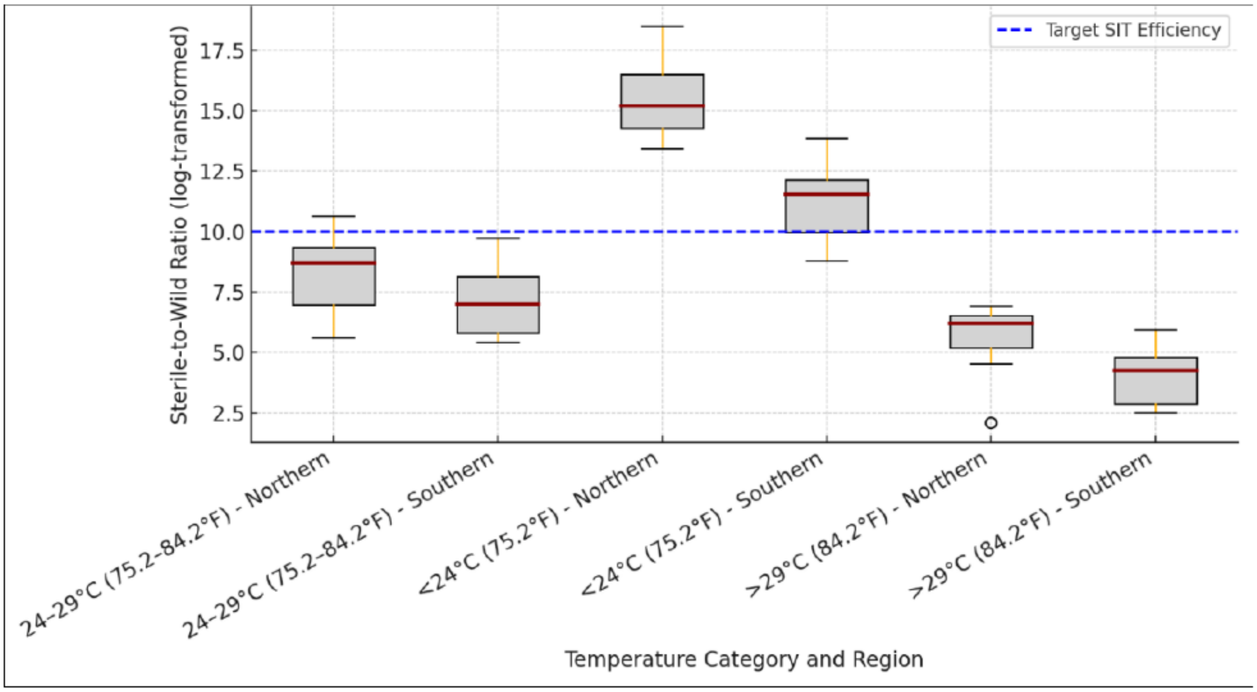

Figure 6. Sterile-to-Wild Fly Ratio by Temperature and Region.
Boxplots display log-transformed sterile-to-wild fly ratios across temperature categories for northern and southern California. Ratios fall below the 10:1 SIT efficacy threshold (dashed blue line) above 29°C (84.2°F), particularly in southern counties.

Although boxplots in Figure 6 show a visible decline, statistical inference from the linear mixed-effects model (Table 1) confirms that sterile-to-wild fly ratios fell significantly below the 10:1 threshold at elevated temperatures. This inferred breakdown in sterile male effectiveness is further demonstrated in Figure 7, which shows a persistent rise in 5-year moving average temperatures in southern California.

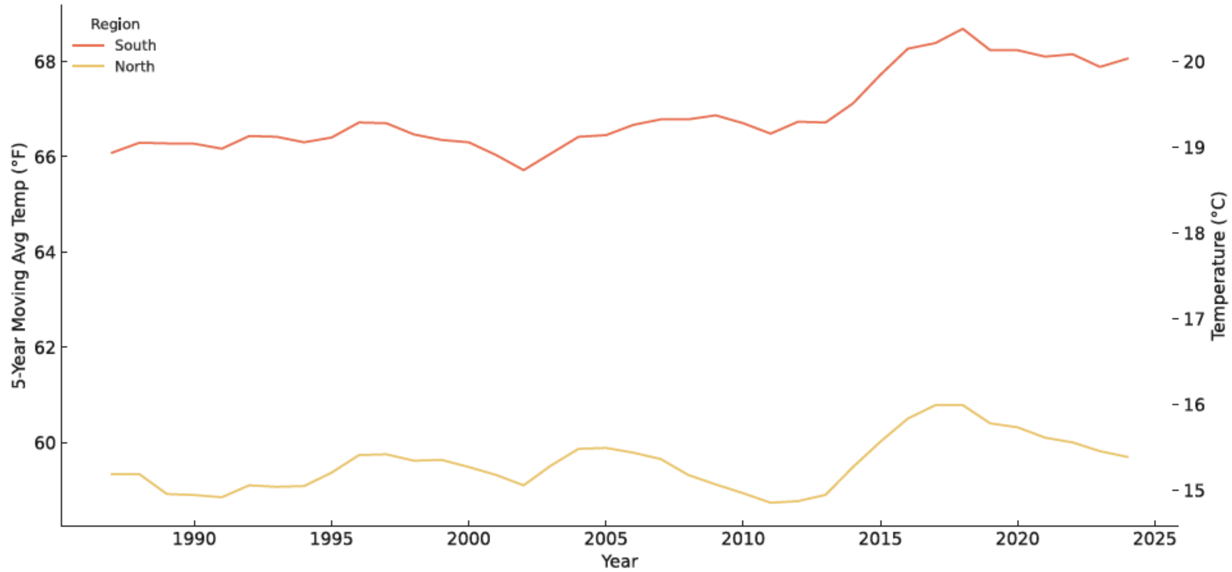

Figure 7. The 5-Year Moving Average of Annual Temperatures by Region (Through Jan 2024, Smoothed).
Five-year moving averages of annual temperature trends show sustained post-2000 warming, especially in southern California. The 2024 endpoint is smoothed using the average of 2021–2023. These trends reinforce concerns about SIT effectiveness under ongoing temperature increases.

As temperatures have warmed post-2000, SIT ratios have correspondingly declined, suggesting that sterile males experience reduced field performance under heat stress. These findings highlight the vulnerability of SIT programs to rising temperatures and demonstrate the need for climate-resilient release strategies.

Objective 3: Regional Differences in Persistence and Potential Adaptation

Wild Medfly counts were consistently higher in southern California across all temperature ranges. As shown in Figure 8, southern counties recorded nearly five times the predicted counts of northern counties at temperatures below 24°C (75.2°F) (southern mean = 0.58 vs. northern mean = 0.13).

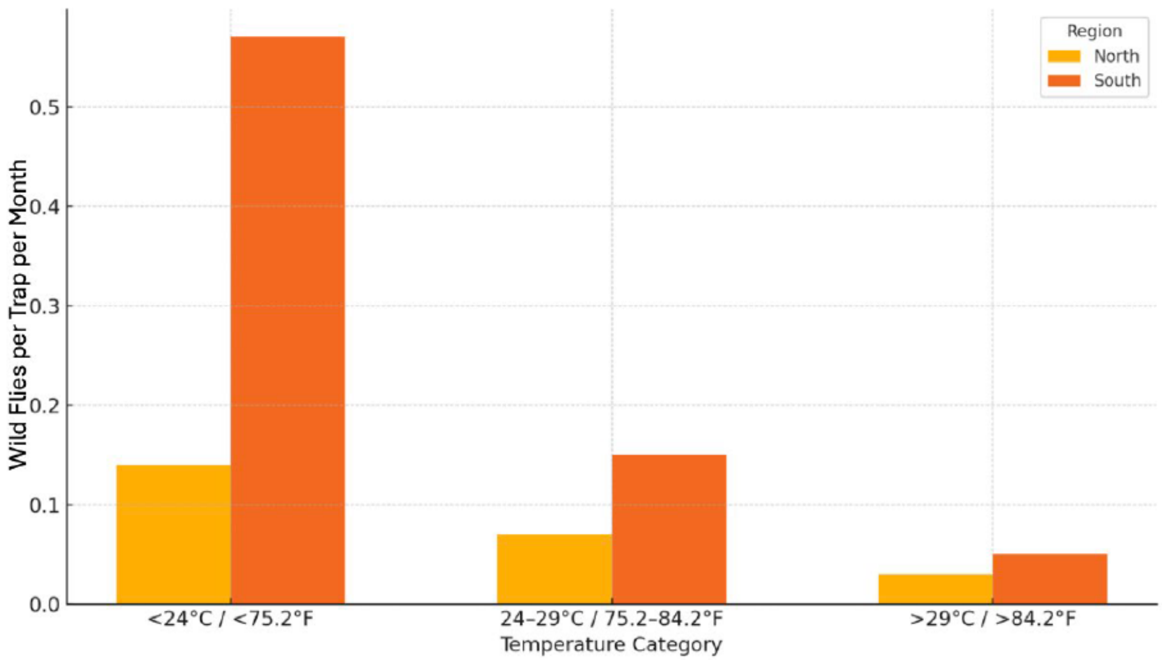

Figure 8. Predicted Wild Medfly Counts per Trap per Month by Temperature and Region. Bar chart showing model-predicted wild Medfly counts (per trap per month) across three temperature categories for northern and southern California. Southern counties consistently exhibit higher predicted persistence across all temperature ranges, including above 29°C (84.2°F).

This regional persistence continued even into the highest temperature category, suggesting enhanced thermal resilience or greater establishment potential in southern populations. The fixed-effects model results (Table 1) confirm significant regional effects ($\beta = 1.3509$, $p < 0.0001$), along with sharp declines in southern wild fly counts above 29°C (84.2°F) ($\beta = -2.7976$, $p = 0.0003$). Occasional wild fly detections in northern counties, such as Alameda and Santa Clara, occurred during cooler months but were not separately modeled. These patterns suggest possible overwintering events or microclimatic refugia in the north. As seen below, Figure 9 shows decade-wise average annual temperatures for each region, revealing that southern California has consistently experienced higher baseline temperatures and a steeper warming trajectory.

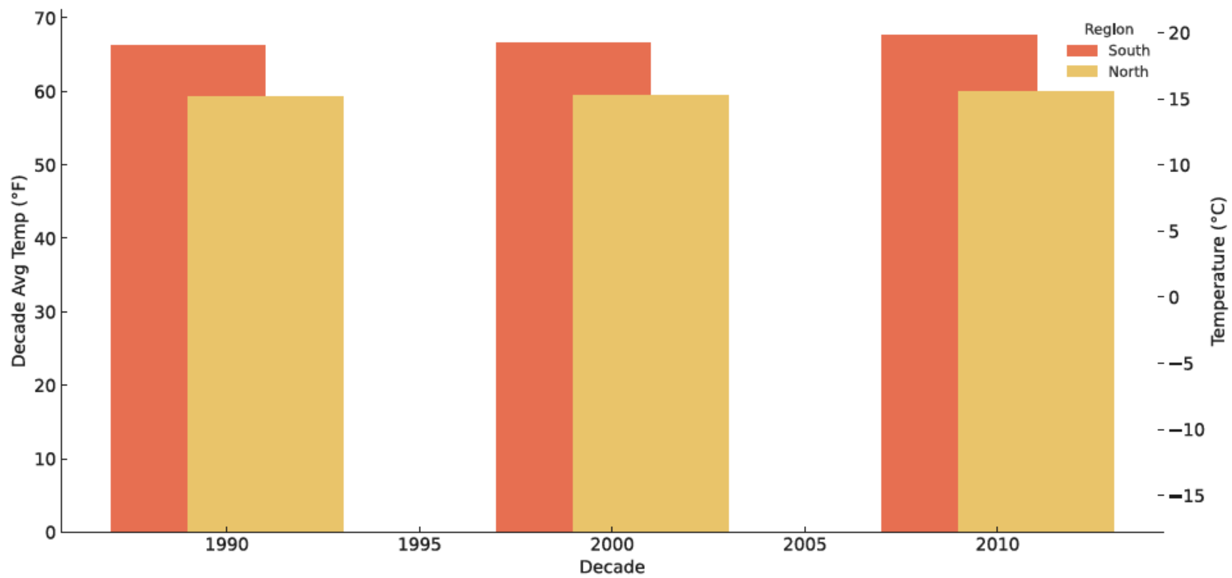

Figure 9. Decade-wise Average Annual Temperatures by Region (Full Decades Only). Average annual temperatures for full decades (1990s, 2000s, 2010s) are shown by region. Southern California exhibits higher baseline temperatures and a steeper warming trajectory compared to the north.

DISCUSSION

Three main findings were identified in my analysis: (1) wild Medfly detections were highest at cooler temperatures and declined as conditions warmed, (2) SIT effectiveness decreased above 29°C (84.2°F), particularly in southern California, and (3) persistent detections in counties like Alameda and Santa Clara suggest possible local adaptation or microclimatic buffering. These results demonstrate how both temperature and geography shape Medfly population dynamics and the success of control efforts.

With objective 1, wild Medfly counts were consistently higher at temperatures below 24°C (75.2°F), aligning with known thermal preferences for development and reproduction (Deschepper et al., 2024; Jaiswal et al., 2023). Counts declined between 24 and 29°C (75.2 and 84.2°F) and were lowest above 29°C (84.2°F). This temperature-linked suppression, although evident, is moderated by the weak correlation with temperature alone, suggesting that factors like humidity or urban microclimates may also influence activity (Wernicke et al., 2024). While this trend held statewide, southern counties continued to report sporadic detections at warmer temperatures. These may reflect local refuges such as shaded, irrigated, or urbanized areas or the emergence of thermally tolerant traits within wild populations.

For objective 2, sterile-to-wild fly ratios dropped sharply at higher temperatures in southern California, indicating reduced SIT efficacy under warmer conditions. This notable decline reveals a critical vulnerability in current control programs, aligning with findings that heat reduces sterile male mating success, lifespan, and competitiveness (Carey et al., 2010; Johnson & USDA, 2023). Sterile males produced in controlled environments may lack the conditioning needed to perform effectively under variable field conditions, particularly in hotter climates. These patterns highlight the need for developing more heat-tolerant sterile strains.

And for objective 3, detection patterns in typically cooler counties like Alameda and Santa Clara challenge expectations that colder regions suppress Medfly survival. Isolated detections during cooler months suggest that some populations may be overwintering or persisting at low densities due to factors like UHIs (Carey, 1992; Papadopoulos et al., 2013), irrigated gardens, or cryptic habitat use (CDFA, 2024; Gilioli et al., 2022). These dynamics may be overlooked in broad-scale management approaches, highlighting the need for region-specific surveillance strategies.

The overall decline in wild Medfly detections from 1987 to 2024 likely reflects improved SIT coverage, targeted outreach, shifting land use, and sustained warming, although the weak correlation with temperature suggests that humidity, irrigation, pesticide exposure, and trap deployment variability also influence trends. Ongoing detections in key counties indicate low-level persistence or periodic reintroductions, especially in urbanized or irrigated environments that buffer against temperature extremes. Figures 5, 7, and 9 illustrate regional temperature patterns over multiple decades, using annual values, moving averages, and decadal means to contextualize long-term warming. Southern California has warmed steadily across all metrics, while the north shows a subtler rise. This consistent warming may reduce Medfly reproduction during peak summer months but also enable survival in formerly unsuitable northern zones. These shifts reinforce the need for SIT programs to adjust release timing, density, and strain selection to match evolving field conditions.

These findings have direct implications for surveillance and control. Identifying key temperature thresholds for wild activity and SIT performance can inform optimal release timing and monitoring priorities (Carey et al., 2017; Syniszewska et al., 2024). Region-specific persistence, particularly in counties like Alameda, Santa Clara, and Los Angeles, further supports the need for tailored eradication strategies that reflect local climate, land use, and microhabitat features (Wernicke et al., 2024; Deschepper et al., 2024). Together, these insights support a transition toward climate-responsive, spatially precise Medfly management in California (CDFA, 2025; Gilioli et al., 2021).

RECOMMENDATIONS

As addressed in Objective 1, wild Medfly densities and seasonal activity fluctuate across biologically meaningful temperature thresholds. Surveillance protocols should be adjusted to reflect temperature-dependent fly behavior. Trap deployment should be intensified during cooler months and in regions where average temperatures regularly fall below 29°C (84.2°F), conditions associated with higher wild fly counts and increased reproductive activity. Improved seasonal targeting can enhance early detection and facilitate more rapid containment of emerging outbreaks (Deschepper et al., 2024; Carey et al., 2017).

In response to Objective 2's assessment of thermal impacts on the SIT, current release protocols should be revised to anticipate temperature-driven declines in sterile male performance. In southern California counties where SIT effectiveness declined at temperatures above 29°C (84.2°F), sterile males should be released earlier in the season, before peak heat, or in greater numbers to offset reduced field competitiveness. Over the long term, California should invest in developing thermally resilient sterile strains that are more conditioned for fluctuating or elevated summer temperatures (Johnson and USDA, 2023; Carey, 2010; Syniszewska et al., 2024).

Based on Objective 3, which revealed persistent wild fly detections in southern California and occasional overwintering events in northern counties, eradication strategies should become more regionally tailored. Counties such as Alameda, Santa Clara, and Los Angeles exhibited persistence under both cool and extreme conditions, suggesting possible thermal adaptation or microclimatic buffering. These areas may benefit from intensified monitoring, more specialized region-specific control measures, and molecular analyses to assess potential genetic adaptation (Deschepper et al., 2024; Carey et al., 2017; Wernicke et al., 2024).

Across all objectives, California's predictive pest models should be updated to incorporate high-resolution climate data, including urban heat island effects, irrigation regimes, and soil moisture variability. These environmental factors influence Medfly persistence but are often omitted from broader-scale modeling platforms such as CLIMEX and MED-FOES.

Including these variables would support more accurate, climate-informed management planning (Syniszewska et al., 2024; Gilioli et al., 2021).

CONCLUSION

Modernizing California's Medfly eradication program through a climate-informed lens is increasingly necessary. Identifying temperature thresholds for wild activity, recognizing when SIT underperforms, and mapping regional persistence all provide actionable insights. As climate change reshapes ecological baselines, Medfly management must evolve from reactive suppression to proactive adaptation grounded in ecological realism and regional precision.

Temperature plays a central role in shaping Medfly population dynamics and directly influences the effectiveness of California's SIT-based eradication strategy. Wild Medfly detections were most frequent at temperatures below 24°C (75.2°F) and declined substantially above 29°C (84.2°F). However, continued detections in southern California, even during warmer summer periods, suggest the presence of microclimatic conditions such as shaded urban areas and irrigated landscapes, or the emergence of thermal resilience among local populations (Wernicke et al., 2024; Syniszewska et al., 2024). Elevated temperatures also seem to reduce SIT efficacy, especially in southern regions. Ratios of sterile to wild flies declined significantly above 29°C (84.2°F), indicating reduced field performance in warmer conditions (Carey, 2010; Carey et al., 2017; Johnson and USDA, 2023). Sterile males developed in climate-controlled facilities may lack the environmental conditioning needed to perform effectively in variable and elevated field temperatures (CDFA, 2025). These findings support the need for revised release protocols and the development of heat-adapted strains capable of maintaining effectiveness as surface temperatures exceed 29°C (84.2°F) (Syniszewska et al., 2024).

Although detections have declined overall, persistent low-level activity in counties such as Alameda, Santa Clara, and Los Angeles indicated that localized survival advantages may be developing. Detections during cooler months further support the role of microclimates and potential adaptation to previously unsuitable conditions (CDFA, 2024; Carey and UC Davis, 2024; Deschepper et al., 2024; Wernicke et al., 2024). While this analysis relied on long-term, passively collected monitoring data with inherent limitations, such as variability in trap placement and occasional data gaps, it provides valuable insights into Medfly ecology across spatial and temporal scales. Temperature-based stratification and regional visualizations (Figures 4 and 5) clarify how fly activity corresponds to thermal conditions. There is higher persistence in southern counties regardless of season, while smoothed temperature trends highlight a sustained warming trajectory through 2024 (Figure 6).

Future research should prioritize genetic profiling to identify traits that allow Medfly populations to persist under thermal stress. These insights could inform the development of strain-specific SIT strategies and improve risk assessments in response to California's changing climate. Although the USDA declared the Medfly eradicated in California in August 2024, 71 wild Medfly detections in Alameda county between August and December of that year (CDFA, 2024) cast doubt on the validity of that conclusion. These detections were officially classified by regulatory agencies as reintroductions, yet Carey (2010, 2024) has repeatedly demonstrated that the Medfly is already established in parts of the state. Framing these detections as reintroductions may delay the transition to long-term, climate-adapted management strategies. Advancing regionally specific, climate-informed eradication efforts will be essential to maintaining the resilience of California's agricultural systems.

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APPENDICES

APPENDIX A

Supplemental Tables and Figures

Table A1. Categories used in Medfly Analysis Counts.

TEMPERATURE (°C / °F)	LABEL USED IN STUDY	INTERPRETATION IN ANALYSIS
<24°C / <75.2°F	Low temperature	Most favorable for wild Medfly activity and reproduction.
24–29°C / 75.2–84.2°F	Moderate temperature	Reduced wild Medfly activity; transitional physiological range.
>29°C / >84.2°F	High temperature	Suppresses wild Medfly activity; considered thermally stressful.

Table A2. CDFA's Medfly Management System and Control Types.

CONTROL TYPE	DESCRIPTION	KEY DETAILS
DELIMITATION	Intensive trapping to map infestation boundaries and monitor post-treatment activity.	High-density traps (ChamP, Multilure, Jackson); fruit sampling; phased trap removal after SIT.
BIOLOGICAL	Release of sterile male Medflies to disrupt reproduction (SIT).	Aerial release of 250,000 flies/sq mi/week in 3.5-mi radius; repeated every 3-4 days for 4-6 months.
CHEMICAL	Targeted application of organic insecticidal bait to kill wild adult flies.	GF-120 Spinosad bait; applied to foliage within 200m; repeated every 7-14 days for 2-3 months.
PHYSICAL	Removal and disposal of host fruit to eliminate potential breeding sites.	Fruit removed from detection sites + 100m buffer; disposed in landfill per regulations.

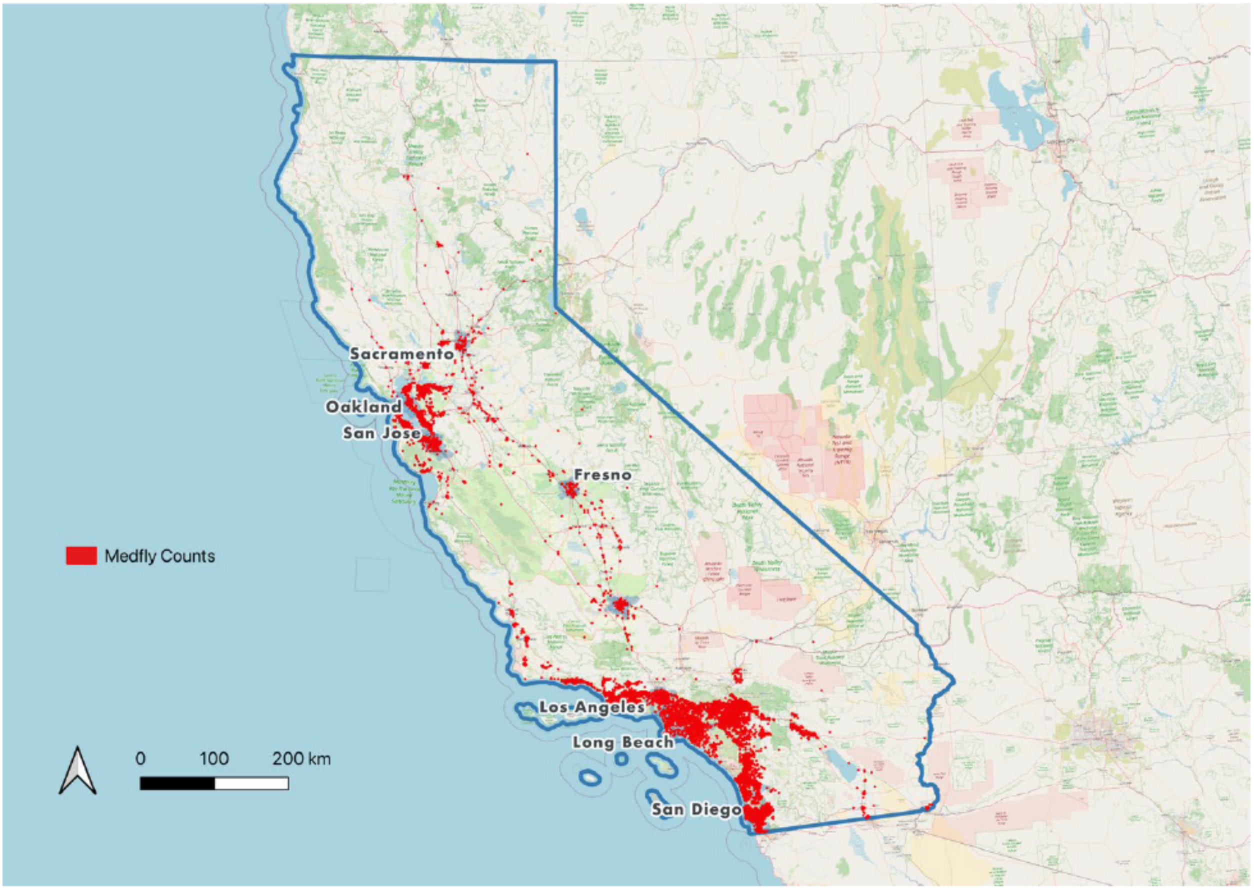

Figure A1. Geographic Distributions of Medfly Detections in California (1987–2024). The cumulative detections of wild and sterile Medflies aggregated over 37 years using QGIS. The map highlights persistent activity in high-risk areas, especially southern California.Though not a statistical result, it provides geographic context for regional patterns discussed in the study. (Data sources: California Department of Food and Agriculture (CDFA), California State Geoportal vector layers, and U.S. Census Bureau TIGER/Line shapefiles).

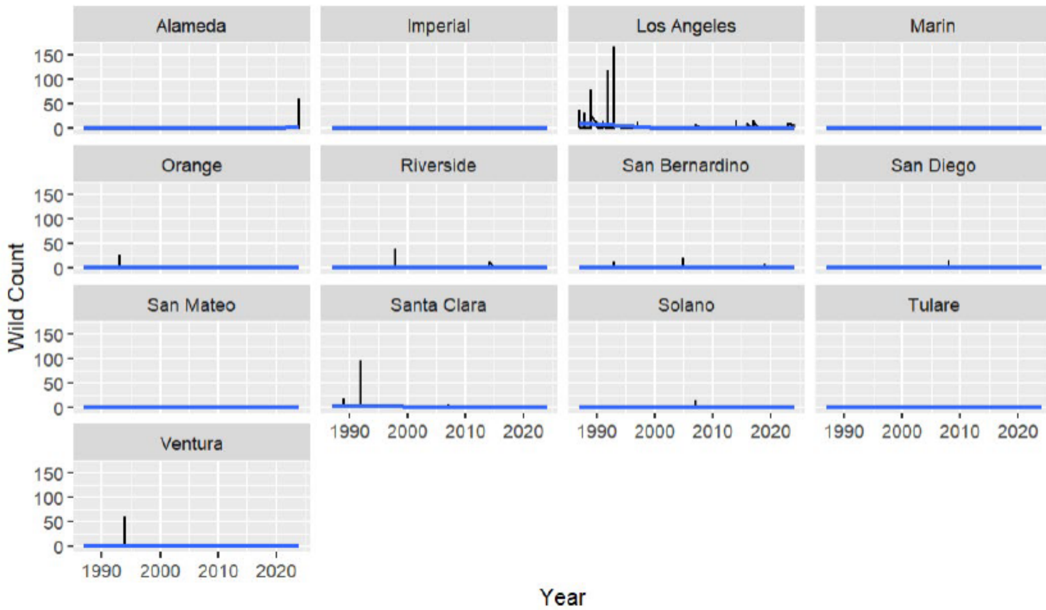

Figure A2. Wild Medfly Counts Over Time by County (Allotey & Owusu, 2025a).
Faceted bar chart of annual wild Medfly detections (1987-2024) across 13 California counties. Most counties show low or sporadic activity, while Los Angeles and Ventura had distinct spikes, especially in the early 1990s. These trends demonstrate regional differences and support county-level modeling.

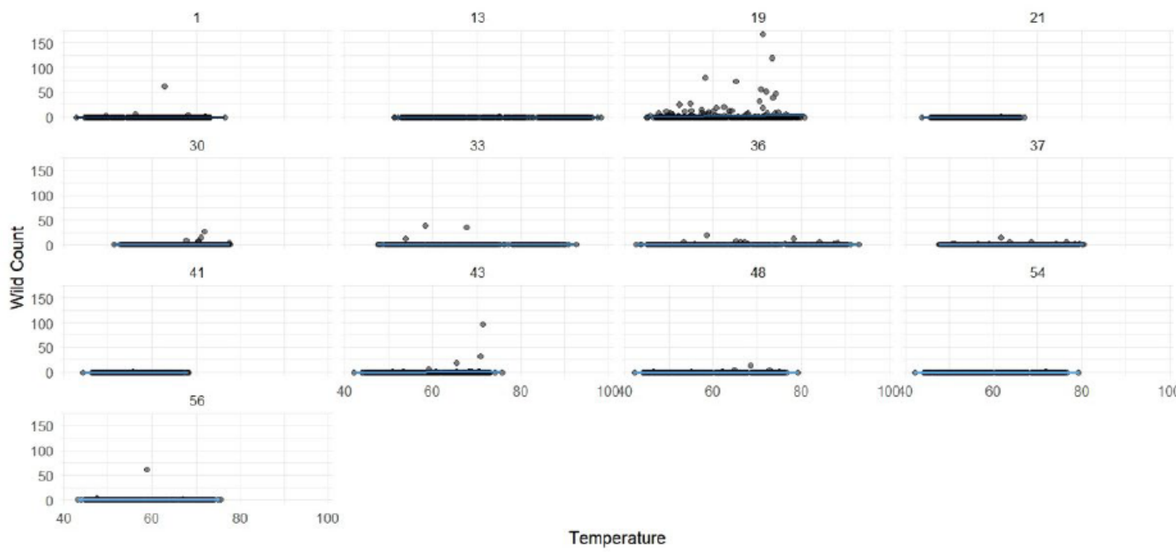

Figure A3. Wild Medfly Counts vs. Temperature by County (Allotey & Owusu, 2025a).
Faceted scatterplot showing monthly wild Medfly counts by average temperature. Most detections occurred below 24°C (75.2°F), while few above 29°C (84.2°F), supporting a negative relationship between heat and Medfly activity.

APPENDIX B

Additional Medfly Figures

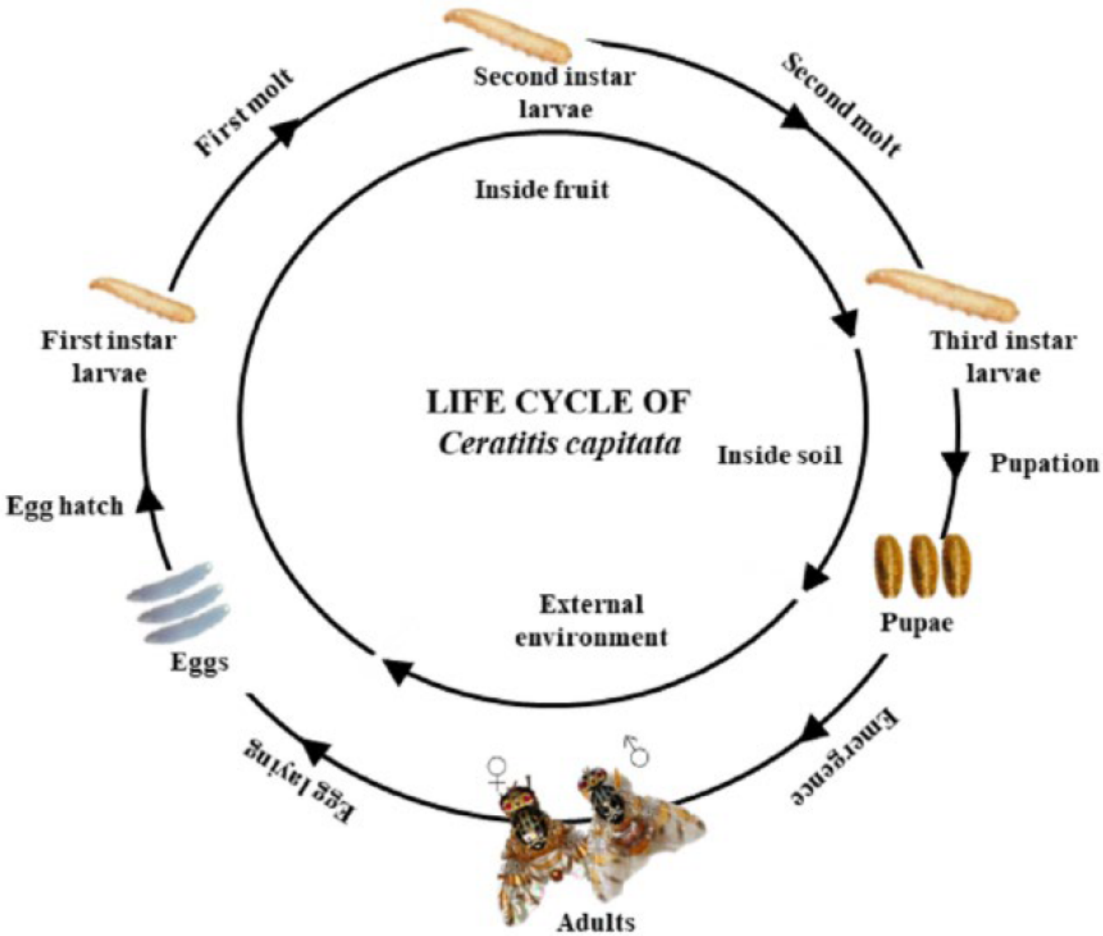

Figure B1. The Medfly Lifecycle (Elqdhy et al., 2024).

Figure B2. Medflies Feeding on Sugar Source (Diamantidis et al., 2011).

Jackson Trap **McPhail Trap**

Figure B3. Medfly Traps (CDFA, 2024).

Figure B4. Sterile Medfly Dyed Pink (Wimbush, 2025).

Figure B5. Medfly Samples Collected From a Los Angeles McPhail Trap.

Figure B6. CDFA Sterile Flies Dyed Pink (CDFA, 2024).

Figure B7. Sterile Medflies Before Aerial PRP Release (Lindenfeld, 2023).