# VSFB Methods

# Study Site

This study was conducted at Vandenberg Space Force Base (34.7398°N, 120.5725°W), located in Santa Barbara County, California, between Point Conception and the city of Santa Maria. The base’s climate experiences mild winters with infrequent frost events (CITE). These climatic conditions, combined with extensive historical plantings of blue gum eucalyptus (Eucalyptus globulus), have created conditions associated with suitable overwintering habitat for monarch butterflies (Danaus plexippus) throughout the installation.

The base contains thirty documented monarch overwintering groves, with several sites consistently ranking within the top 10% of population counts statewide over the past decade (Xerces Society 2025b). These groves are predominantly characterized by mature blue gum stands with canopy heights reaching 45 meters. Grove structure varies considerably across the base. Spring Canyon contains eucalyptus trees naturally distributed along a perennial creek corridor, creating a heterogeneous canopy structure with variable tree spacing and understory vegetation. In contrast, the UDMH site consists of eucalyptus planted in distinct linear rows as windbreaks, resulting in uniform spacing and minimal understory development. The restricted access of the military installation protected our equipment from vandalism and unauthorized disturbance throughout the study period.

To identify suitable monitoring locations, we initially selected thirteen overwintering groves based on two primary criteria: documented capacity to support clustering monarchs (defined as aggregations of more than five individuals roosting in close proximity) and year-round accessibility for equipment deployment and maintenance. Site selection was conducted in collaboration with the base's monarch conservation coordinator, who provided local expertise derived from managing Western Monarch Thanksgiving Count activities for multiple years (J. Griffiths, personal communication, 2023). This collaboration ensured selection of sites with the highest probability of monarch occupancy based on historical observations and local environmental conditions.

**[Figure here showing all thirteen groves, with different symbology for the various subsets]**

Equipment deployment strategies differed between monitoring seasons to accommodate evolving research objectives and field experience. During the 2023-2024 season, we adopted an adaptive sampling approach, deploying equipment opportunistically at sites with confirmed active monarch aggregations. This approach concentrated monitoring efforts at Spring Canyon and UDMH, where butterflies were observed throughout the season. We also deployed equipment at sites where monarchs were anticipated based on habitat characteristics but not yet observed, including additional locations within Spring Canyon and UDMH, as well as exploratory deployments at SLC-6 and Tangair. These anticipatory deployments yielded minimal data due to lack of monarch occupancy.

For the 2024-2025 season, we modified our approach to establish monitoring stations at ten sites before monarch arrival, based on historical occurrence records compiled by the base conservation coordinator (J. Griffiths, personal communication, 2024). This expanded spatial coverage was designed to capture greater environmental variation across potential overwintering sites and reduce bias toward historically productive locations. However, the 2024-2025 season coincided with historically low monarch abundance throughout California (Xerces Society 2025a), resulting in no observed clustering behavior at any monitored location on base. Consequently, our final dataset was restricted to three sites, Spring Canyon, UDMH, and SLC-6, that produced analyzable data during the 2023-2024 season.

# Field Equipment

To collect data on butterfly abundance throughout the overwintering season, we deployed remote monitoring equipment near monarch butterfly clusters at overwintering sites. Field observations were conducted using 15-meter telescoping fiberglass poles (Max-Gain Systems, Inc., Marietta, GA). Each pole was anchored at three points using ground anchors with guy lines securing both the top and base to create a stable, freestanding structure. Poles were positioned between 4 and 17 meters from cluster locations to provide clear vantage points while minimizing disturbance to the butterflies.

We monitored monarch abundance using modified trail cameras (GardePro E7 and E8, Shenzhen, China) configured for near-infrared imaging to enhance contrast between clustering butterflies and surrounding vegetation. Hardware modifications included replacing the mechanical infrared cut filter with clear glass to allow all wavelengths to pass through the sensor, and disconnecting the mechanical switch to prevent automatic mode switching. Additionally, near-infrared pass filters (>850 nm) were cut to size and mounted on the lens exterior to restrict incoming light to near-infrared wavelengths only. This modification produced images where clustering butterflies appeared as dark masses against the bright reflectance of living eucalyptus foliage in the near-infrared spectrum.

Cameras were mounted at the top of poles using lightweight tie-down straps and positioned horizontally toward butterfly clusters at their roosting height. The wireless live view feature allowed for real-time preview and precise camera aiming during deployment. We configured cameras for time-lapse mode with 10-minute intervals between captures, with motion detection disabled. This interval was selected to balance high temporal sampling frequency with battery life constraints, following preliminary field tests that showed minimal butterfly position changes within 10-minute periods while maintaining approximately 30-day battery life under continuous operation.

Wind monitoring equipment consisted of Rain Wise WindLog Wind Data Loggers (Rain Wise Inc., Trenton, Maine) installed at the apex of each pole. These instruments recorded average wind speed and maximum wind gust at one-minute intervals. This configuration allowed wind measurements at heights approximating butterfly roosting locations, providing data on microclimate conditions that may influence cluster dynamics.

We defined discrete monitoring periods as deployment units for analytical purposes. Each deployment represented a unique combination of monitoring location, camera configuration (including mounting height and viewing angle), associated wind measurements, and temporal coverage period. This deployment-based structure allowed us to account for variation in environmental conditions and equipment configurations across different monitoring efforts while treating each deployment as an independent sampling unit in subsequent statistical analyses.

A tree with a measuring device and a diagram

AI-generated content may be incorrect.

# Image Analysis

## Grid-based Counting Method

To quantify changes in monarch butterfly abundance from collected imagery, we developed a systematic grid-based counting protocol that balanced accuracy with the practical constraints of analyzing tens of thousands of images. This approach addressed the challenge of estimating abundance in large aggregations where individual counts would be prohibitively time consuming. We subdivided each image using a grid overlay system, where human labelers could assign order-of-magnitude estimates per cell. Grid dimensions remained fixed throughout each deployment to ensure consistency. To facilitate this labeling effort, we developed custom software using the Electron framework in JavaScript.

Grid cell size varied by deployment based on camera-to-cluster distance. Cell dimensions were optimized to ensure most occupied cells would contain butterflies in the 10-99 count range, balancing classification efficiency with spatial resolution. This standardization minimized the occurrence of cells alternating between widely different order-of-magnitude categories across the time series.

## Counting Protocol

Human labelers estimated butterfly abundance within each grid cell using four order-of-magnitude categories: 0 (no butterflies), 1-9 (single digits), 10-99 (dozens), and 100-999 (hundreds). Labelers were trained using a comprehensive online guide that included example images for each category and detailed classification criteria. The protocol prioritized efficiency while maintaining consistency across observers.

Classification guidelines emphasized counting only visible butterflies without estimating hidden individuals in overlapping clusters. For cells containing partial butterflies at grid boundaries, labelers included these in counts unless double-counting would cause an adjacent cell to move to a higher category. When butterfly counts in a cell fluctuated between categories across the time series, the lower estimate was consistently applied to provide conservative abundance estimates.

In addition to estimating monarch abundance, labelers were asked to record if the cell was in direct sunlight or not. This measurement was recorded only if the cell was occupied and was stored a separate value.

Labelers received ongoing feedback throughout the classification process. All classifications were reviewed for common errors including mislabeled cells, incorrect category assignments, and inconsistent application of counting criteria. We communicated corrections directly to labelers to ensure consistent application of the protocol.

## Abundance Calculation

We calculated an abundance index for each frame by summing the products of cell counts and their assigned category values across all grid cells. This index employed conservative estimates using the minimum value within each order-of-magnitude category:

where represents the number of cells in category , and represents the conservative estimate for that category. We used minimum category values (C₁ = 1 for category 1-9, C₂ = 10 for category 10-99, and C₃ = 100 for category 100-999) rather than midpoint or maximum values to ensure our temporal analyses reflected genuine population changes rather than estimation uncertainty.