# 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. 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 (Xerces Society 2025b). In addition, the restricted access of the military base facilitated long term deployment of our equipment by minimizing disturbance from unauthorized individuals.

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. For example, 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.

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 (Xerces Society 2025b, 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 research objectives and field experience. During the 2023-2024 season, equipment deployment followed two strategies: (1) targeted deployments at sites with confirmed monarch presence, and (2) anticipatory deployments at locations where monarchs were expected based on historical data but not currently observed (J. Griffiths, personal communication 2023). Targeted deployments were concentrated at Spring Canyon and UDMH where active aggregations were documented throughout the season. Anticipatory deployments were made at four overwintering sites: additional locations within Spring Canyon and UDMH, plus SLC-6 and Tangair. No monarchs were recorded at any anticipatory deployment sites, and these data are not included in this study.

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 not captured in our 2023 season. 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 two sites, Spring Canyon and UDMH, during the 2023 season only.

# Field Equipment

To observe changes in monarch abundance in response to strong wind events, 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 opportunistically between 4 and 17 meters from cluster locations. Location of poles balanced ground conditions, infrastructure clearance, and optimal viewing angles while minimizing butterfly disturbance.

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 involved exploiting the camera's internal filter-switching mechanism by triggering the nighttime mode to engage the clear glass filter position, then disconnecting power to the switching mechanism to prevent reversion to the infrared cut filter. 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.

To systematically organize our heterogeneous monitoring efforts and create consistent analytical units, we defined discrete monitoring periods as deployment units. Each deployment represented a unique combination of monitoring location, camera configuration (including camera ID, mounting height, and viewing angle), associated wind measurements, and temporal coverage period. Since equipment was frequently reused across different locations and time periods, this deployment-based structure provided named units of sampling effort that allowed us to account for variation in environmental conditions and equipment configurations while treating each deployment as an independent sampling unit in subsequent statistical analyses. This approach produced time-series images from each deployment, which we used to estimate monarch cluster abundance over time through systematic grid-based counting methods. These abundance estimates could then be analyzed in relation to wind speed measurements and other environmental variables recorded at each deployment location.

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. This approach also emulates the manner in which abundance estimates are collected by field researchers, including those conducting the annual Thanksgiving Count (Xerces Society 2017). 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 (https://kylenessen.github.io/monarch\_trailcam\_classifier/). The protocol prioritized efficiency while maintaining consistency across observers.

Because abundance estimates were derived exclusively from two-dimensional photographic images, our classification protocol focused on quantifying only butterflies visible in the image plane without attempting to estimate the three-dimensional structure or depth of clusters. This approach intentionally excludes hidden individuals positioned behind visible butterflies in overlapping aggregations, providing a conservative but consistent measure of cluster size that reflects the observable surface area of each aggregation rather than its total volume. 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. Direct sunlight classification presented challenges because the oversaturated conditions eliminated the contrast that made butterfly detection possible in shaded areas. Labelers were instructed to classify cells as receiving direct sunlight when branches or butterflies exhibited additional illumination that was clearly direct rather than indirect light, even when individual butterflies became difficult to distinguish due to pixel oversaturation. This classification required careful attention to subtle shape recognition and maintenance of contextual awareness about butterfly locations established from previous images in the time series. This measurement was recorded only if the cell was occupied and was stored as 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 shifts in categories rather than estimation uncertainty.