

Supplemental Information to accompany “Computer Vision-Based Population Monitoring of Immobile Synchronous Firefly Swarms” in: Biodiversity and Conservation

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Supplemental: Computer Vision Details

Details of each computer vision step:

1. Recordings were done with a DSLR camera (Sony-RX10 IV), producing video files in the MPEG-4 Part 10 (H.264 / AVC) format at a resolution of 3840 x 2160 pixels and 25 frames per second (XAVC S 4K with maximum bitrate). Uncompressing and converting of frames to the HSV model was done with the commercial software Matlab version 2022b (as was all coding for subsequent steps).
2. We determined reasonable thresholds for each component of the HSV images based on tests with five sample videos chosen to have varied background lighting and varied locations. We first manually examined HSV levels for the pixels representing firefly flashes, then ran tests of our automated code isolating a single component for threshold variation. For example, we varied the hue lower threshold from 0 to 70 (out of 360) while holding the hue upper threshold constant at 70, the saturation thresholds constant at [0.2, 1], and the value thresholds constant at [0.6, 1]. We then plotted the number of fireflies detected as a function of the varying threshold. We interpreted a plateau on that graph as indicative of a reasonable threshold value and established “tight” and “loose” bounds for

each threshold in that way. After this process, we finalized thresholds for monitoring as: hue in [59/360, 71/360], saturation in [0.19, 1.00], and value in [0.60, 1.00], inclusive.

3. For spatial clustering we used DBSCAN (density-based spatial clustering of applications with noise), an established and efficient method that performs well on our data (Ester et al., 1996). We also considered the circular Hough transform (Duda & Hart, 1972) but rejected it because of its poor computational efficiency (run times approximately thirty times slower than DBSCAN) with no discernible performance benefit. Regardless of which method is used, when fireflies appear very close together in an image or occlude one another, detection errors occur due to the clustering algorithm agglomerating multiple individuals into one cluster. We do not think this was a significant source of error in our data, however, because the fireflies typically leave significant amounts of space between them when flashing.

4. In the first nonempty frame of each video, we assign a unique ID to each cluster that is detected. To maintain IDs across frames, we forecast future positions² and then, in the subsequent frame, the cluster that is located closest to the forecast position is taken to represent the same firefly, with the important caveat that the distance from the forecast position be less than a threshold value (which we establish via empirical trials in our monitoring dataset at 60 pixels). If no cluster is observed close enough to the forecast position, the firefly is assumed to have stopped flashing. Forecasting and comparison to new clusters continues onward into future frames. After a maximum number of frames F_{max} have passed without a new observation, a previously observed cluster may be deemed to be no longer relevant, and the relevant ID “retired” so future observations of it are no longer allowed (this may occur, e.g., if a firefly stops flashing and then flies away). In practice, for video clips of 1-2 minutes like those used in this monitoring project, we found that this step was not necessary, but for longer videos we believe it improves accuracy.

5. There is the possibility that some spurious observations pass our HSV threshold filters: e.g., artificial lights, or flashes from other firefly species. We distinguish true, useful observations of the species of interest (*P. malaccae*)

via three dynamical criteria: (a) total number of frames where firefly is observed ($2 < N < 30\%$ of total video frames); (b) typical flash duration ($2\% < dur_{tot} < 30\%$ of frames where firefly was present); and (c) number of consecutive frames in which a given cluster is observed ($consec_frames < 5$). Additionally, a very small number of clips (2 of 281) included spurious reflections that we removed via masking before processing those clips.

Supplemental: Details of Bootstrapping Procedure

We estimate uncertainty in the following manner. The majority of clips (261 out of 281) are repeated one or more times (i.e., we capture the same swarm on the same date at nearly the same time in more than one video). These repeated clips allow us to employ bootstrapping to learn about the distribution of any given statistic we extract from a video—most importantly firefly abundance. We construct samples by selecting from all repeated clips (with replacement) 10,000 times.

Example: let us image that, for one date, we have a single swarm with a video clip repeated three times. We randomly choose one of those three clips and compute the firefly abundance, then repeat 10,000 times. This gives us, for each date, 10,000 abundance estimates. We take the mean of those 10,000 as our best estimate of the true abundance, and we calculate the quantiles for a desired 95% confidence interval to learn about the uncertainty in our estimate.

When there are multiple swarms present on a given date (as is typical), the process is slightly more complicated. We generate samples by selecting one clip from each swarm with at least two clips, then summing swarm abundances to get a total abundance for the day. We repeat that 10,000 times then compute the mean and 95% confidence intervals for that sample. If there are swarms with non-repeated clips present, we compute the best estimate abundance over all swarms as the previously computed mean plus the non-repeated swarms' abundances. We make the assumption that uncertainty is similar for those non-repeated swarms, and hence compute the final confidence intervals by extrapolate their relative sizes from the sample subset with repeated clips (for which we have a distribution with 95% confidence intervals) to full abundance estimate.

Example: Consider three swarms, two of which have twice-repeated clips; label the clips A1, A2, B1, B2, C. We use computer vision to compute swarm abundances N_{A1} , N_{A2} , N_{B1} , N_{B2} , N_C , then generate a sample set S_{rep} of size 10,000 by repeatedly computing $N_{A_i} + N_{B_j}$, where i, j are selected uniformly and independently at random from $\{1, 2\}$ for each element of the sample set. The best estimate for firefly abundance summed over repeated clips, N_{reptot} , is then the mean of S_{rep} , and 95% quantiles $[N_{0.025}, N_{0.975}]$ are also computed from this sample set. Finally, the total

firefly abundance is estimated at $N_{\text{tot}} = N_{\text{reptot}} + N_C$, and confidence intervals are estimated as $[N_{\text{tot}} - N_{\text{tot}} / N_{\text{reptot}} (N_{\text{reptot}} - N_{0.025}), N_{\text{tot}} + N_{\text{tot}} / N_{\text{reptot}} (N_{0.975} - N_{\text{reptot}})]$.

Our bootstrapping code and data are available at <https://doi.org/10.21985/n2-12hg-gj05>.

Supplemental: Additional Details on Field Site Layout

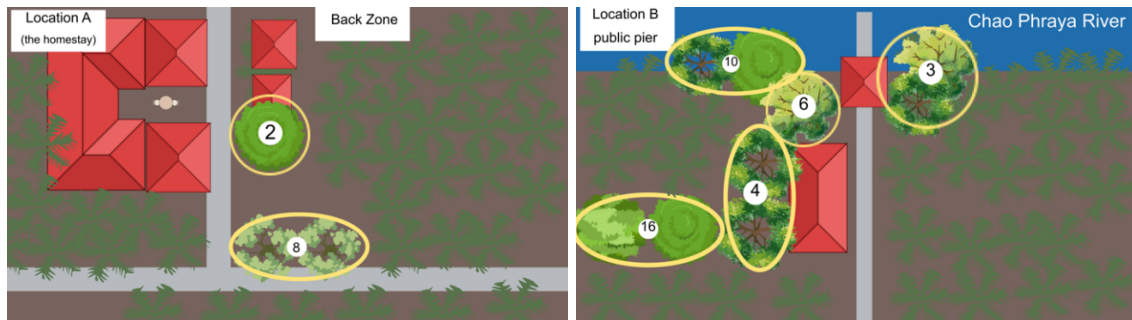


Figure S1: Additional field site diagrams. Note that Figure 1, panel (c) of the main text shows the diagram of the front zone for Location A.

Supplemental: Firefly Abundance Data

Date	Mean group size (2.5%, 97.5%)
09-Mar-2023	133.8 (103.5, 167.2)
30-Mar-2023	174.3 (139.6, 211.8)
18-Apr-2023	29.5 (17.4, 41.6)
01-May-2023	90.7 (64.7, 116.1)
15-May-2023	302.3 (270.6, 334.5)
01-Jun-2023	666.4 (623.3, 708.6)
13-Jun-2023	478.1 (422.0, 534.0)
07-Jul-2023	227.6 (185.9, 264.3)
04-Aug-2023	224.0 (195.3, 252.4)
25-Aug-2023	64.5 (58.0, 71.0)
20-Oct-2023	190.7 (158.0, 222.0)
19-Nov-2023	103.5 (82.0, 125.0)
03-Dec-2023	93.0 (69.0, 117.0)
20-Dec-2023	108.0 (95.0, 121.0)
26-Jan-2024	183.5 (167.0, 200.0)
22-Feb-2024	210.7 (176.0, 243.0)

Table S1. Firefly abundance data. This is the data plotted data in Fig. 2a.

Supplemental: Additional Weather and Environmental Data

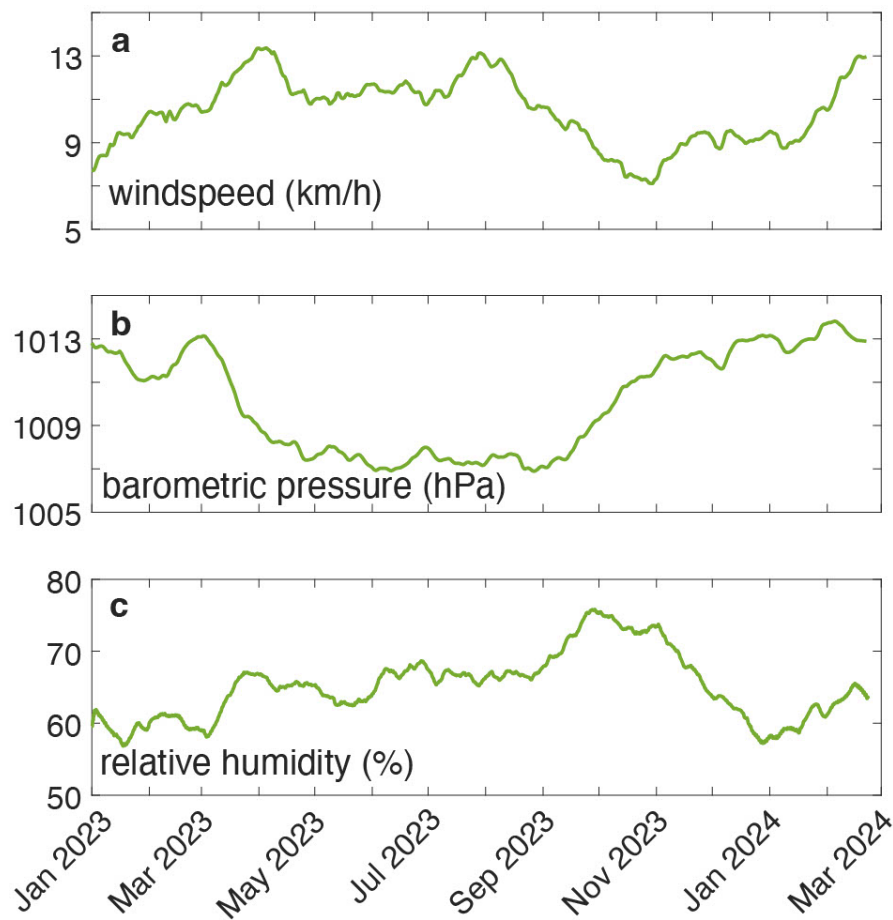


Figure S2. Additional climate variables. Climate data from January 2023 through March 2024 (to account for the full life cycle of the fireflies that were active in the peak in June 2023). We compare the local (a) daily average windspeed, (b) daily sea level air pressure, and (c) is the relative humidity measured twice hourly.

Supplemental: Annual Firefly Flash Frequency Variation

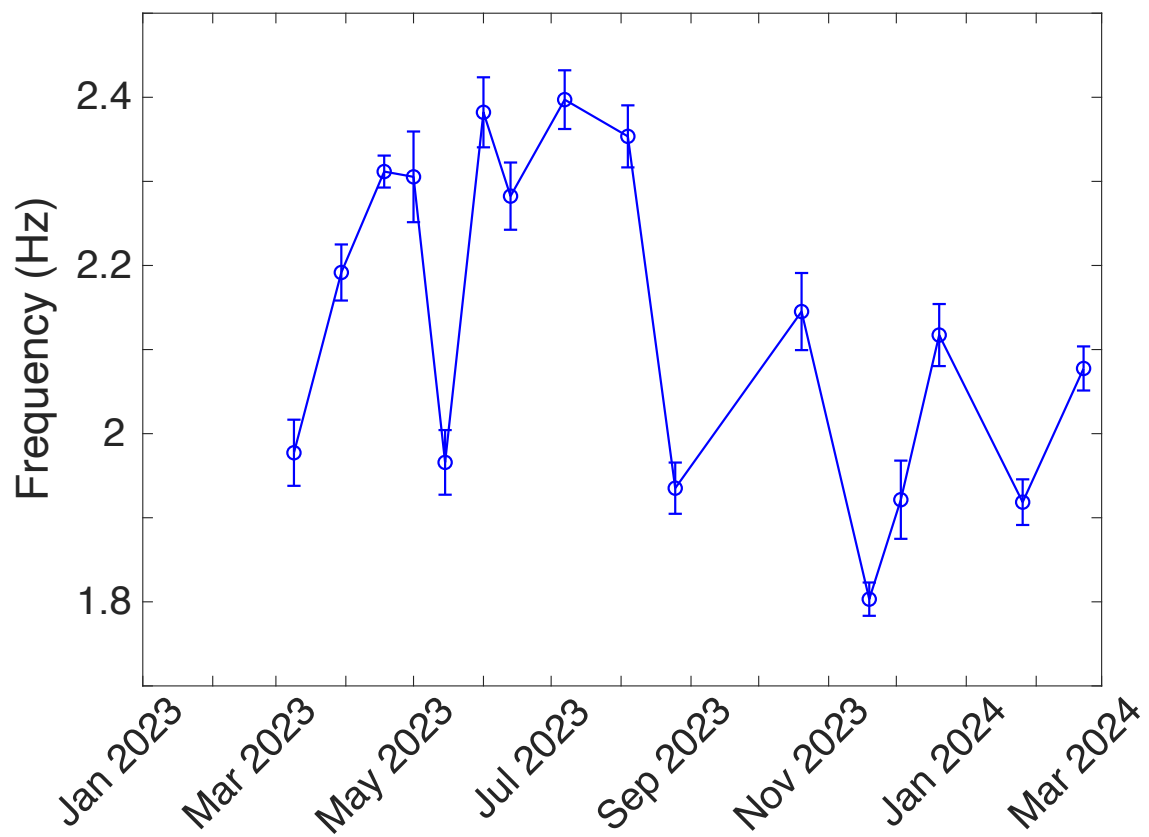


Figure S3: Firefly flash frequency over time. Open circles represent mean flashing frequencies of fireflies pooled by date. Error bars represent typical standard deviation of firefly frequency (averaged over all swarms recorded on that date).