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Remote Sensing Pelagic Species via Aerial Systems

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Executive Summary

Context

Oceans Unmanned (OU), a 501(C)(3) non-profit organization provided manned aircraft and Unmanned Aircraft Systems (UAS) field operations in support of California Department of Fish and Wildlife's (CDFW) marine California Coastal Pelagic Species Survey (CCPSS) between 1st February 2022 and 31st July 2024. Three field deployments occurred to explore the feasibility of novel payloads and imagery techniques intended to augment the ability to accurately identify species remotely and estimate biomass of nearshore schools of Pacific sardine (sardine) and northern anchovy (anchovy). This report provides the methodology, results, and a feasibility synopsis, including recommendations for updating current survey methods and areas for future exploration.

Historical Perspective

Since 2012, CDFW has conducted the aerial CCPSS to document sardine and anchovy in nearshore waters of the Southern California Bight, and expanded the survey area to cover nearshore waters off Northern California beginning in the summer of 2017. Surveys currently utilize trained spotters for biomass estimates. While efforts to evaluate visual bias and variance between observers are ongoing, there is growing concern regarding survey sustainability. Skilled observers require many years of training and CDFW is often limited by observer availability and associated costs. Advances in photogrammetric cameras, other sensors, and computer software allow for the potential to develop and apply a more rigorous and repeatable biomass estimate calculation to ensure standardization of long-term datasets. A previous agreement between OU and CDFW initiated the exploration of RGB and multi-spectral UAS imagery in 2021 through 2022, and this project has been informed by that experience, and provides a continuation of that effort.

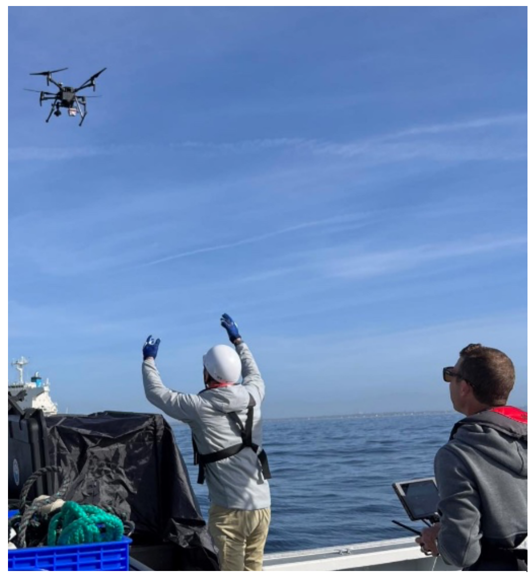

Figure 1 – Field operations with vessel-based UAS operations in 2021.

Summary of Objectives

1. Calculate the relative size/volume (e.g., biomass) of Coastal Pelagic Species (CPS) schools from areal extent by utilizing the historical survey non-nadir RGB imagery catalog and observer estimates, and/or other spatial datasets, and document the methodology used to do so;
2. Mobilize to different regions of the state to search for CPS in coordination with CDFW partners, established CPS aerial surveys, and commercial CPS fishing vessels;
3. Obtain georeferenced photogrammetric and sensor-based imagery including RGB images and multi-spectral sensory data of CPS using an unmanned aerial system platform from an at-sea research vessel and/or through a system on an aircraft;
4. Estimate the areal extent (surface area) of CPS schools from imagery and document the methodology;

5. Determine the maximum angle at which imagery can be acquired to still provide an accurate and repeatable areal extent of objects detected.
6. Provide spatially referenced data including, but not limited to, surface areas, spectral characteristics, bathymetry, scale, resolution, altitude, and image tags as a data package to allow for examination of observed CPS in relation to other spatial datasets;
7. Provide high-quality georeferenced spectral and RGB imagery that capture the entire areal footprint of CPS schools; and
8. Determine the feasibility of using spectral data either exclusively or in conjunction with spatial or temporal metrics to distinguish individual CPS and determine school size (e.g., biomass). Document these results and if use of spectral signatures to define composition is not feasible, provide information on additional resources or expertise that may be required.
9. Develop recommendations for a production flow to collect imagery and field observation that can be scaled up for use in an aircraft.

Key Findings

- It is feasible to collect imagery of CPS schools using a nadir mounted aerial camera on a manned aircraft
- It is feasible to collect imagery of CPS schools using a nadir mounted aerial camera on an unmanned aircraft system
- it is possible to utilize photogrammetric techniques to accurately measure surface area of CPS schools from aerial imagery
- Utilizing historical and newly acquired data it is possible to correlate surface area to CPS school biomass by using linear regression analysis to model the relationship
- Nadir imagery for photogrammetric analysis is preferable, however non-nadir imagery with no more than 30° offset from vertical can still be successfully processed with minimal errors
- Weather (glare and sea state) are a constant challenge that technical improvements to imaging systems (multi-camera setups, IR and ND filters) may allow for more efficient data collection in future efforts.

Recommendations for Next Steps

- Future research should be focused on aerial photogrammetry-equipped manned aircraft and closer coordination with the trained spotter and fishing vessels to collect as much imagery combined with biomass estimates and ground-truthed measurements as possible
- More data is required to refine the relationship between surface area and CPS school biomass to define a reliable model
- Further funding and research is required to determine optimal imaging system, data collection strategy and workflows
- More data is required to determine feasibility of utilizing spectral imagery to identify species composition of CPS schools

Background

OU facilitates the use of unmanned technologies and promotes their safe and environmentally responsible operation to protect the ocean and coastal marine environment. OU has years of experience with both unmanned and manned aircraft operations for various research and resource protection agencies, including supporting the National Oceanic and Atmospheric Administration (NOAA) Remote Sensing Division, as well as prior collaborations with CDFW on CPS.

Figure 2 – Vessel-based UAS operations in 2021 and 2022 informed the scope of this project.

This project builds on top of findings from the 2021 and 2022 project, P2070011: Using Remote Sensing via Unmanned Aerial Systems to Survey Marine Coastal Pelagic Species, which found that multi-image photogrammetry for CPS schools was practically unfeasible, while single-image photogrammetry held promise, but required more data and methodology development. Additionally, it was concluded that historical manned-aircraft imagery could be leveraged to extract data useful to inform methodologies and define the relationship between aerial image surface area and estimated biomass.

Field Operations Approach

Overview

For this project, aerial imagery was captured using both manned and unmanned aircraft while simultaneously collecting school tonnage estimates from a trained spotter, while also attempting to collect fishing validation data point-sets. Data collection was planned to be coordinated with scheduled manned aerial surveys and a trained spotter to provide direct comparisons to current biomass estimation methods on certain field sessions. Additionally, coordinated fishing validation point-sets for ground truthing remotely sensed data were attempted.

A rugged boat-launch multicopter UAS equipped with two separate payloads for testing and evaluation was utilized. Additionally, smaller, RGB-only platforms were used for quick reconnaissance flights to locate and confirm the presence or lack of CPS schools. Imagery was collected with both sensors and analyzed to determine and develop potential procedures and protocols for detection and measurement.

Three field sessions provided opportunities for iterating on imaging methodology, and post-processing techniques across a variety of environmental conditions.

Field Operations

Field operations were scheduled on-demand in coordination with the CDFW lead scientists. Fieldwork was based out of the CDFW Monterey field office, with OU crew deployed to these locations. Having multiple field deployments enabled the iteration and improvement of methodologies, and allowed the collection of data in a variety of environmental conditions. Three field deployments, each 2-5 days in duration were conducted, summarized in Table 1. On the first and third deployments, OU's Cessna Skylane 182 was deployed out of Gilroy, CA. The manned aircraft spotted CPS schools, captured photographs, and relayed location information to the vessel to coordinate simultaneous UAS imagery collection.

Similarly, a second operation out of Monterrey deployed a manned aircraft with photographer and trained spotter, along with vessel-launched UAS ops, and a fishing vessel for point-set validation data. A 2-person UAS crew from OU accompanied CDFW on a small vessel for boat-launched operations. The small vessel and manned aircraft maintained communications using a handheld aeronautical band VHF radio.

Date	Ops Type	Location
5/31 - 6/4 2023	Manned aircraft w/ trained spotter	Monterrey, Half Moon Bay
5/17 - 5/23 2024	Manned aircraft w/ trained spotter/UAS/Fishing Vessel	Monterrey
6/26 - 6/27 2024	Manned aircraft w/ trained spotter/Fishing Vessel	Monterrey

Table 1 - Field deployments overview

Maritime Best Practices and Environmentally Conscious Operations

OU has extensive experience working aboard research vessels and with boat-launched maritime UAS operations. OU has developed and maintains a Maritime Operations Best Practices manual (available on request) and adhered to these approved guidelines.

In addition, OU has a strong environmental ethic and always seeks to do no harm when operating UAS and manned aircraft. Our Environmentally Conscious Operations program, ECO-Drone, documents best practices to avoid and minimize wildlife disturbance and seeks to educate and raise awareness in the UAS and drone pilot community. As always, the ECO-Drone best practices were followed, including the observation and documentation of wildlife responses to our UAS operations by a CDFW biologist. All operations were conducted in accordance with all applicable law, including the National Marine Sanctuary Act, the Marine Mammal Protection Act and the Endangered Species Act.

Figure 3 – Crew preparedness and field testing at Monterrey Bay.

Operational Environment

All UAS operations were conducted between surface and 400 ft Above Ground Level (AGL) during daylight, Visual Flight Rules (VFR) conditions. Visual line of sight was maintained on all flights. All flights occurred within the limitations of Federal Aviation Administration (FAA) Part 107. Airspace of all flights was verified with FAA, and NOAA, for proper authorization for UAS operations below 400 ft. A NOAA permit was required and secured for UAS operations in the Monterey Bay National Marine Sanctuary. The Low Altitude Automatic Notification Capability was used to get clearance while operating in the airspace of Monterey Regional Airport.

All OU manned aircraft operations were conducted under FAA Part 91, daylight, VFR conditions from either the Watsonville Municipal Airport (KWVI) or Monterey Regional Airport (KMRY). The area of operation was less than 5 miles offshore between Monterey and Santa Cruz at altitudes between 950 and 1500 feet AGL. A minimum separation of 500' was maintained with the CDFW aerial survey aircraft during concurrent flights operations.

Coordination with CDFW Crews

Scheduling of field work required close coordination with CDFW aerial survey crews, as well as fishing validation crews during field operations. Conducting simultaneous CDFW aerial survey observations of CPS study schools was valuable in comparing and evaluating new aerial imaging survey methodologies and results with traditional aerial survey data. Field notes were crucial to positively correlate observations and data sets. UAS data were collected, tagged, and catalogued in the field to facilitate this connection. Aviation and marine weather, communications, and mechanical issues all presented logistical challenges during this research phase that should be improved upon in future efforts to ensure as much correlated data can be collected as possible.

Figure 4 – Point-set fishing validation attempt photographed from manned aircraft with trained spotter.

Methodology

UAS Platform

The DJI Mavic 3 Enterprise UAS platform was selected as the primary aircraft for this project. OU has 5+ years of experience utilizing the Mavic line for maritime operations. This platform has proven to be reliable in harsh conditions, and stable for vessel launch and landing. The weather resistant hull, 30+ minute flight time, hand launch and recovery capability, make this the UAS of choice for this research. The M3E has an integrated high-resolution photogrammetric RGB camera with 4/3 CMOS sensor supporting 20 megapixel images. While the M3E was the primary data collection platform, the OU team also utilized the DJI Phantom 4 Pro as a reliable quad-copter with 19 minutes of flight time and 20 megapixel RGB payload for some flights.

OU Manned Aircraft Platform

A Cessna Skylane 182 was used for aerial image capture. Outfitted with a custom installation of a calibrated 100-megapixel Hasselblad A6D aerial survey camera and a Vector Nav VN-200 Inertial

Measurement Unit, the aircraft was able to capture imagery and metadata suitable for single-image photogrammetry of CPS schools. For certain flights, the backup Nikon D800 with Zeiss lens mapping camera system was used.

Table 2 contains a comprehensive summary of all flights from all field sessions.

Figure 5 and 6 – Cessna Skylane 182, and Hasselblad A6D.

Image Collection

The image collection methodology was informed by learnings from past efforts in 2021 and 2022. Key learnings from prior art include:

- Live feed imagery from UAS was typically insufficient to locate schools.
  - Manned aircraft observations are the most reliable way to locate schools.
  - Bird and mammal activity are useful indicators to locate CPS schools.
- Survey grid missions, with many overlapping images, failed to stitch into an orthomosaic due to the dynamic environment of moving water and shifting schools.
  - Single image photogrammetry encompassing an entire school holds the most promise.
- Image collection must be accompanied by a trained spotter estimate to correlate school area to biomass estimate.
  - The gold standard would be to also incorporate a fishing point-set for ground truthing school biomass.

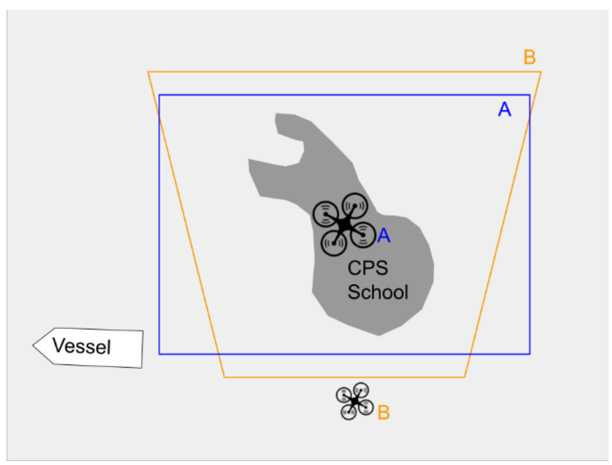

Figure 7 - Concept of nadir imaging with UAS in position A, and with blue image footprint A. And, non-nadir image with UAS in position B, and with orange image footprint B.

For this project, UAS and manned aircraft imaging focused on capturing the entire extent of CPS schools in single RGB images. Multispectral imaging capabilities were planned, but given the lack of good opportunities in the field, only RGB imagery was collected. Schools were located by manned aircraft, photographed and estimates made by the trained spotter. Once a school had been positively identified, and in proximity to the vessel, the UAS was launched. The UAS was flown over the CPS school and multiple images were taken from various altitudes, up to 400' ASL, and multiple off-nadir angles (see Image 1). Entire schools were captured in single images to be used for single-image photogrammetry.

All field operations avoided the 4 hour window centered around solar noon to minimize sun glint in nadir imagery. While also accounting for weather, often times with a stratus cloud layer in the mornings, the window of opportunity for good photography was limited to the late afternoons. This weather pattern occurred on 7 of the 11 scheduled field days.

Field and Flight Log

Date	Flight No	Aircraft	Start time	End time	Notes
6/1/23	M1	Cessna Skylane 182	1015		Devin's plane down for maintenance. Ragged ceiling at 1500'. Rendezvous with CDFW vessel/UAS ops. No confirmed CPS schools.
6/3/23	M2	Cessna Skylane 182			Devin piloting. Pat spotting. Julie photographing. Low ceiling. Anchovy schools imaged #230603_103 through 201. 80 ton sardine school pictured in 230603_258.
5/17/24	U1	MAVIC 3E	1330	1352	Training flight from CDFW vessel
5/17/24	U2	MAVIC 3E	143	1455	Devin overhead with multiple schools of fish at an average of 8 tons but nothing visible on UAS imagery do to poor water clarity and rough weather
5/18/24					No UAS operations as plane arrived later on scene and weather deteriorated. No fish observed by plane
5/19/24					No UAS operations as plane arrived later on scene and weather deteriorated. No fish observed by plane
5/20/24	U3	P4	1351	1407	Plane observed anchovy with Triumpho on scene. Estimated at (6) tons. Hard to see in UAS imagery due to poor water clarity and choppy conditions. Vessel breaks and no set is made
5/21/24					Plane delayed due to fog and low clouds. Once plane was in the air and transited to survey area, heavy winds and seas present, no fish observed
5/22/24					Plane delayed due to fog and low clouds. Once plane was in the air and transited to survey area, heavy winds and seas present, no fish observed
5/23/24					Vessel broken and high winds forecast all day, no operations
6/26/24	M3	Cessna Skylane 182			Low weather until noontime. Some fish seen, but glare prevented nadir photography.
6/26/24	M4	Cessna Skylane 182			Afternoon flight, wind came up and white caps, no fish.
6/27/24	M5	Cessna Skylane 182	1105		Several schools near Moss Landing buoy, from 5 to 25 tons with photographs.
6/27/24	M6	Cessna Skylane 182	1615		Several passes from MRY to Santa Cruz. No fish observed.

Table 2 – Flight details

Historical Image Analysis

In coordination with CDFW, OU examined over 1000 archived images for those which satisfied the following criteria:

- Low non-nadir tilt angle (>30°)
- Encompasses entire CPS school
- Accompanied by spotter pilot tonnage estimate
- Accompanied by altitude and camera sensor and lens metadata

The vast majority of images reviewed did not meet the necessary requirements. The small number of images that satisfied the above criteria were analyzed using the same single-image photogrammetry methodology as the novel aerial imagery collected as part of this study.

Post-Processing

Single-image photogrammetry is the process of orthorectifying a single image so that distance and area based measurements can be made. While this process is prohibitively complex over varied terrain, with the assumption that all of our images are of flat water at sea-level, the process is simplified and provides reasonable approximations of linear and area measurements.

A subset of images were analyzed using a single-image photogrammetry technique and utilizing ImageJ software from the National Institutes of Health (NIH), originally developed as a medical imaging analysis tool to enable making 2D measurements. Using ImageJ, individual photos were used to make area measurements of CPS schools which were captured in a single image.

Image processing, through the use of tools like Adobe Lightbridge and ImageJ threshold coloring showed promise in delineation of CPS schools. Further development of image enhancement techniques could yield more benefits and efficiencies in surface area measurements.

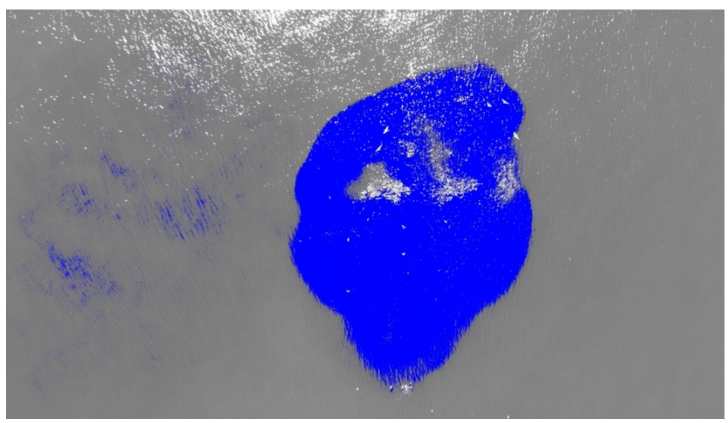

Figure 8 – Color thresholding in ImageJ aids in school delineation.

For images taken with the camera at nadir (-90° from the horizon), the GSD is a function of the sensor size, image size, and altitude. The barometric altitude was captured in image metadata from all of the UAS and manned aircraft camera systems utilized for this work. Generally, taking images at nadir isbest practice, and all efforts were made to collect images as such while also getting clear and distinguishable imagery of the schools. Often, given the solar elevation, and resulting sun glint, someangle away from nadir was required to avoid glint and capture clear images of CPS schools.

For non-nadir images (oblique gimbal angle) the GSD is not consistent across the image footprint, and a logarithmic factorization was calculated to compensate for the larger GSD at the top of the image, as the angle deviates from nadir. This factor will increase exponentially as the gimbal angle deviates from nadir, so this methodis suitable for nadir and near-nadir (< 30°) photos for quick and scalable area estimates.

Once the GSD was calculated, the number of pixels per linear unit was entered into ImageJ. Subsequently, ImageJ provides the functionality to draw polygons around areas of interest and will calculate the area.

The same post-processing methods were used for historical image analysis.

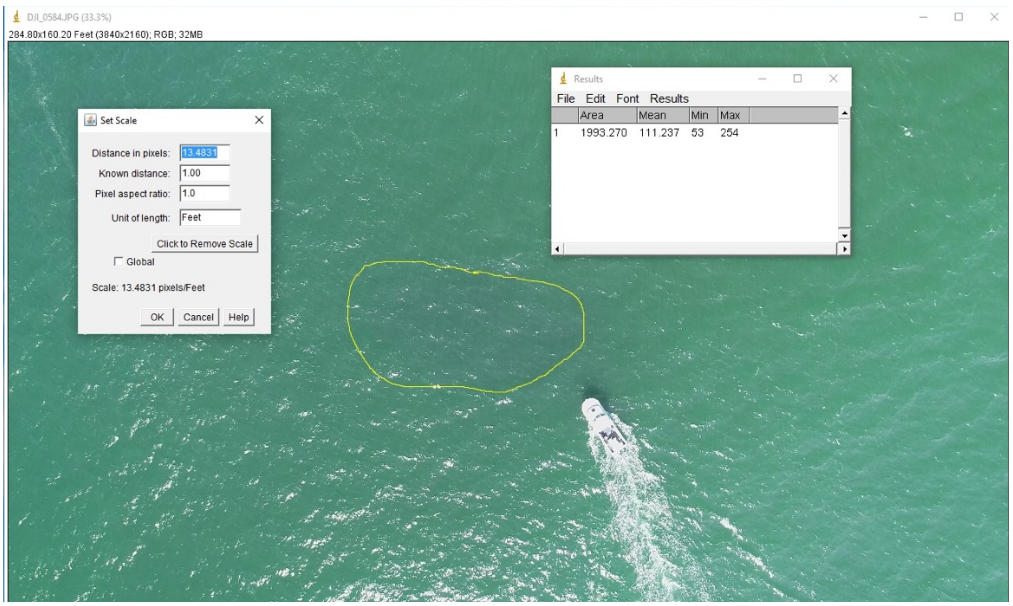

Figure 9 - Nadir image of anchovy school analyzed in ImageJ.

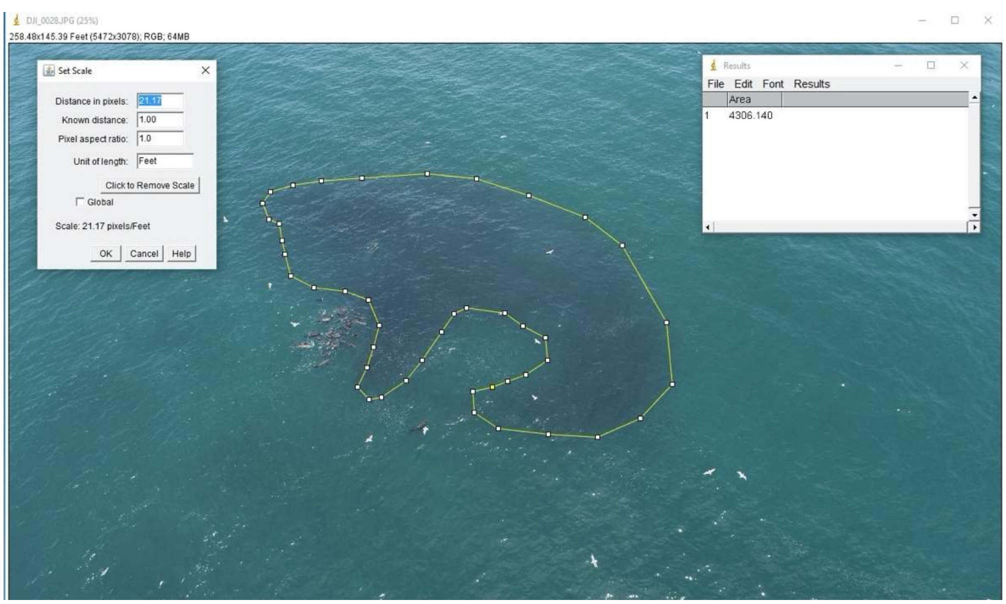

Figure 10 - Non-nadir image of anchovy school analyzed in ImageJ.

Results

Individual images were analyzed using the methods described above, and CPS school surface areas were calculated. Table 3 contains details of images processed using single-image photogrammetry. While no point set data was captured to truly ground-truth these results, trained spotter observations were simultaneously captured for the schools used in these analyses.

Photo #	Date	Spotter Estimate (metric tons)	Altitude (ft/MSL)	Camera	Dataset	Notes
DJI 0028 Spotter	5/25/22	65	144	DJI X4S	Oceans Unmanned UAS Survey	
DJI 0060 Spotter	5/25/22	80	137	DJI X4S	Oceans Unmanned UAS Survey	
Img00017039	6/8/19	65	1500	Nikon D700	CPS Historical Data	The same school assessed with two different images to correlate consistency in methodology.
Img00017050	6/8/19	65	1500	Nikon D700	CPS Historical Data	Consistent results between the two photos of the same fish
Img00002893	5/14/14	35	939	Nikon D700	CPS Historical Data	Image chosen due to clear outline of fish school and multiple images of the same schools. School tonnage has been aggregated for the (2) schools represented in the images.
Img00002894	5/14/14	35	942	Nikon D700	CPS Historical Data	Same school as image above and similar results on tons estimated
Img00011615	5/29/14	3	945	Nikon D700	CPS Historical Data	Very small school and depth should be considered differently
Img00017160	6/5/14	90	1102	Nikon D700	CPS Historical Data	Image taken at significant angle and fish are close to the shoreline
DJI_0028	5/20/24	6	325	DJI Phantom 4	Oceans Unmanned UAS Survey	Image from UAS with estimate from Devin and the F/V Triumpho in frame
HalfMoonBay_ 230603_258.jpg	6/3/23	80	731	Nikon D850	Oceans Unmanned Plane Survey	Image from Skylane 182 and Devin estimate

Table 3 - Summary of Single-Image Photogrammetry analyzed images

Images from historical analysis, manned aircraft, and UAS were combined into a single dataset and regression analysis performed to model the relationship between surface area and biomass. These sparse observations were plotted and a best-fit linear regression was applied, shown in Figure 11. With y-intercept pinned to 0, a linear factorization shows R^2=0.726. Of course, this relationship should be regarded with some caution, and more data points are needed to refine a formula for estimating biomass from aerial imagery area measurements. Results with the spotter estimate beside the modeled biomass are shown in Table 4.

Image	Date	Area (m2)	Spotter Estimate (metric tons)	Modeled Estimate (metric tons)
DJI 0028 Spotter	5/25/22	400.04	65	20.16
DJI 0060 Spotter	5/25/22	555.83	80	28.01
Img00017039	6/8/19	1871.33036	65	94.32
Img00017050	6/8/19	1877.64771	65	94.63
Img00002893	5/14/14	1032.7945	35	52.05
Img00002894	5/14/14	1125.97547	35	56.75
Img00011615	5/29/14	38.5544407	3	1.94
Img00017160	6/5/14	1584.72687	90	79.87
DJI_0028	5/20/24	216.926793	6	10.93
HalfMoonBay_230603_258.jpg	6/3/23	528.335191	80	26.63

Table 4 - Summary of Spotter Estimates to Area Estimates

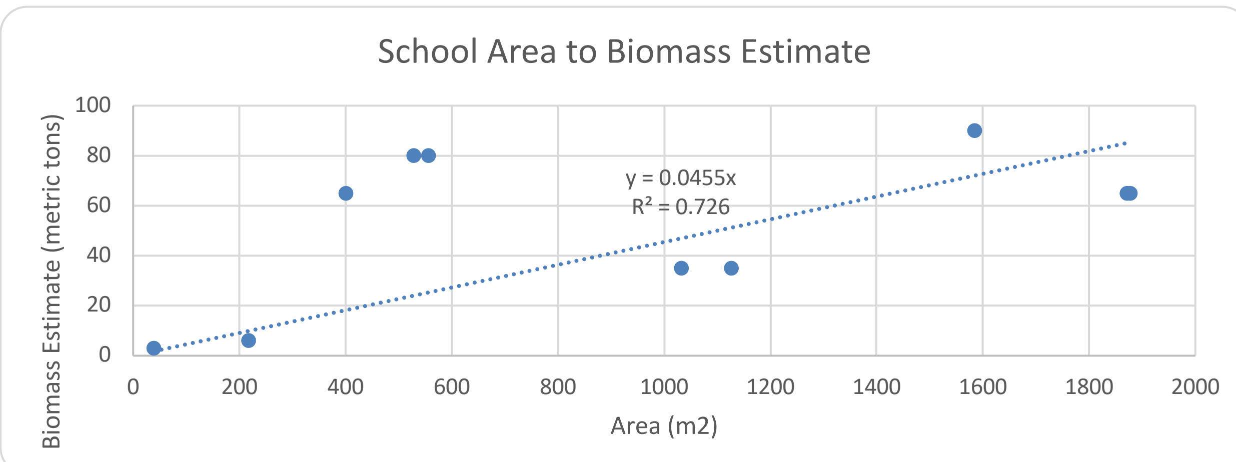

Figure 11 - School Area to Biomass Estimate linear regression

For nadir and near-nadir images these methods represent a quick and repeatable method to estimate surface area.

Only nine data points of co-collected aerial spotter estimates with imagery were gathered; the gold standard is to have point-set data ground truthed. As part of this field work, attempts were made to co-collect point-set fishing validation numbers. However, on this project, those attempts were not successful in gathering data, and future efforts should strive to collect these valuable data. Additionally, no bathymetry data were collected, and future point-set validation should include depth measurements to enable characterization of biomass in relationship to area and water depth.

Feasibility Synopsis

- Coordination between the trained spotter, manned aircraft, UAS vessel, and fishing vessel posed serious challenges to collecting the necessary data for this project. Fishing vessel validation data is paramount to establishing the relationship between aerial imagery school area and true biomass.
- Historical imagery is a valuable source of CPS imagery, and when accompanied by spotter pilot estimates, can help to establish the relationship between spotter pilot estimates and school surface area using single-image photogrammetry.
- Further data are required to develop variables for deriving volume from calculated surface area and incorporate bathymetry for both anchovies and sardines. This includes continued work with both a spotter pilot and fishing vessels to correlate and ground truth estimates.
- Linear regression analysis on a small dataset provides an unbiased method to estimate biomass from surface area without the need for a trained spotter. Human factors in trained spotter observations may introduce significant error into biomass estimates. In addition, unmodeled factors like school depth and density may be secondary variables that may improve current modeling efforts. Additional datapoints will greatly assist in refining this model going forward.
- UAS have proven to be a viable test bed for evaluating sensors and developing data collection and processing techniques; however, due to current regulatory and technical constraints, the use of UAS for state-wide surveys is still a few years away from realistic implementation. Therefore, further research should continue with opportunistic data collection from UAS platforms and sensors, with present focus on manned aircraft.
- Manned aircraft hold value over UAS for surveying large areas, and potentially state-wide scale. Belly-mounted nadir-only camera systems in manned aircraft present challenges to photographing schools while also avoiding solar glint and quickly capturing imagery in a dynamic environment. Belly-mounted cameras should have a real-time heads-up viewfinder, and may also benefit from a maneuverable gimbal or a multi-camera setup. Handheld photogrammetric cameras may have the benefit of being more maneuverable in real-time to capture usable imagery in the dynamic environment.
- Further research and data are required to refine methodology to ensure accurate, repeatable measurements. Further research includes multi-sensor payloads, optimum camera angles, weather conditions, solar angle, ND and IR filters, and altitudes.
- Even with an airplane, at the end of the day, fishing is challenging. Aeronautical weather, marine weather, water turbidity, location, and the presence of fish all contribute to the difficulty of collecting actionable imagery.

Next Steps and Future Experimentation

- Collect aerial imagery in concert with point-set fishing validation data. Capture bathymetric data to incorporate water depth into biomass modeling.
- Continued exploration of historical photo catalog to identify images appropriate for single-image photogrammetry and analyze for refined area to trained spotter biomass modeling.
- AI Convolutional Neural Networks have been shown to have some ability to correctly detect individual fish (see Oceans Unmanned, “P2070011: Using Remote Sensing via Unmanned Aerial Systems to Survey Marine Coastal Pelagic Species”, June 30th, 2022) and further exploration in this field holds promise to develop software systems capable of turning large amounts of aerial imagery into actionable data.
- Explore species discrimination and school delineation with a larger dataset and compare costs

and capabilities side-by-side between multi-spec and RGB analysis.

- Explore multi-camera/sensor solutions for manned-aircraft surveys and UAS proxies, including directgeoreferencing mapping systems.

Conclusion

Aerial imagery, from both manned and unmanned aircraft, has proven to be a valuable tool to carry out proof-of-concept testing and methodology development for surveying CPS. The data collected as part of this project is a valuable step towards correlating trained spotter observations to CPS area measurements and points the way towards the future. Moving towards a consistent methodology for year over year comparisons while eliminating observer bias will result in better stock assessments. Continued development on the work presented here holds promise in informing updates to current surveying methodologies for population estimates and serves to contribute to the sustainable, data-informed management of California's CPS.

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List of Attachments

1. Single-Image Photogrammetry Results (../Data/Photogrammetric Analysis.xlsx)
2. Analyzed Images Dataset (../Images/*)