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RESEARCH

Surveying Waterfowl Broods in Wetlands Using Aerial Drones

Desmond A. Mackell*[1], Michael L. Casazza[1], Cory T. Overton[1], Kevin J. Buffington[2], Chase M. Freeman[2], Joshua T. Ackerman[1], Karen M. Thorne[2]

ABSTRACT

Effective waterfowl management relies on the collection of relevant demographic data to inform land-management decisions; however, some types of data are difficult to obtain. For waterfowl, brood surveys are difficult to conduct because wetland habitats often obscure ducklings from being visually assessed. Here, we used Unoccupied Aerial Systems (UAS) to assess what wetland habitat characteristics influenced brood abundance in Suisun Marsh, California, USA. Using a thermal-imaging camera, we surveyed 17 wetland units that encompassed 332 ha of flooded area on the premises of seven waterfowl hunting clubs during the waterfowl breeding season. Additionally, using a combination of multi-spectral imagery collected from the UAS flights and LiDAR data from the previous year, we mapped habitat composition within each unit to relate to brood observation counts. From June 3–7, 2019, we identified 113 individual broods comprising 827 ducklings. We found a positive relationship between the number of broods observed and the proportion of the unit that was flooded. We also found a positive relationship between the number of broods observed and the area of effective habitat—a metric of flooded habitat within two times the 95th-percentile Euclidean distance that all broods were observed from any vegetated cover. Brood surveys using UAS could complement the traditional Breeding Population Survey and provide local managers with fine-scale and timely information about shifts in brood abundance in the region.

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Data Accessibility: The datasets generated during the current study are available in the ScienceBase repository (Mackell et al. 2024).

KEY WORDS

waterfowl, brood, duck, duckling, drone, Uncrewed Aerial Vehicle, Uncrewed Aerial System, UAS, UAV, brood survey

INTRODUCTION

Wetlands are an important habitat type for a variety of species, including breeding waterfowl in North America. However, the United States has experienced considerable losses of these important ecosystems (Dahl 1990; Brophy et al.

2019). California wetlands, specifically, have been greatly affected as a result of the direct conversion of wetlands into agriculture, urban and industrial development, and water diversion (Frayer et al. 1989). By the 1980s, California had lost approximately 90% of its historic wetlands (Dahl 1990). Within the San Francisco Bay-Delta estuary, Suisun Marsh is the largest existing contiguous brackish marsh, and one of the largest brackish marshes in the western United States (CVJV 2020). The marsh is also host to one of the densest breeding waterfowl nesting sites in California and is of particular importance to breeding Mallards (*Anas platyrhynchos*), Gadwall (*Mareca strepera*), and Cinnamon Teal (*Spatula cyanoptera*) (McLandress et al. 1996; Ackerman et al. 2014).

Monitoring waterfowl populations is an integral part of understanding population dynamics, setting harvest regulations, and measuring the effect of conservation efforts such as those outlined in the North American Waterfowl Management Plan (Humburg et al. 2018). In California, breeding waterfowl population trends are largely measured through traditional breeding population surveys, where observers count adult breeding pairs from fixed-wing aircraft along pre-defined transects. These pairs are usually counted in the spring during the California Department of Fish and Wildlife's annual Waterfowl Breeding Population Survey, hereafter Breeding Population Survey (Skalos and Weaver 2019). However, such methods do not include nest success or brood production and survival, which are important factors that contribute to population recruitment rates (Hoekman et al. 2002; Rönkä et al. 2011). Age class ratios during winter from hunter-harvested ducks and band returns are used to determine recruitment rates beyond the Breeding Population Survey (Bellrose et al. 1961; Iverson et al. 2004), but often lack the spatial and temporal resolution that local managers need to understand the brood rearing dynamics of their wetland system. In this regard, nest and brood surveys can be used in addition to large-scale population surveys to better understand the population dynamics of local breeding waterfowl (Stevens et al. 2003; Carrlson et al. 2018).

Many bird species are suitable for aerial surveys that utilize thermal imaging to monitor populations (Bird et al. 2020; Stander et al. 2021). This may be particularly true in wetland habitats where there is often the presence of open water, and the contrast between cold water and warm bodies may increase detections (Bushaw et al. 2020). Duckling brood surveys in Suisun Marsh could provide insight into local habitat quality that the Breeding Population Surveys may not capture. For example, alignment of habitat available to breeding adults during nest initiation does not regularly match what is available to broods later in the breeding season when they move out of the nesting uplands. Schacter et al. (2021) found that the extent of flooded wetlands in Suisun Marsh decreased between 73% and 86% from April to July, indicating large changes in habitat availability. The traditional Breeding Population Survey is conducted each year in April for Suisun Marsh (Skalos and Weaver 2019), meaning there are likely to be large decreases in water availability between the survey (during nest initiation) and the brood rearing period. These reductions in water availability can often be exacerbated during drought years and through management activities, underscoring the need to measure how these reductions affect breeding waterfowl in the region. Furthermore, brood surveys have been used to measure the success of wetland restoration projects in providing breeding habitat for waterfowl (Stevens et al. 2003; O'Neal et al. 2008). Brood surveys can also provide researchers and managers with another tool to assess waterfowl populations that can be incorporated into adaptive management plans (USBR 2013).

Non-invasive and remote monitoring tools have gained interest in recent years. For example, a recent study used drones paired with infrared thermography to study humpback whales (Horton et al. 2019). These types of technological advancements may be particularly important for elusive or shy species. Therefore, advancements in Unoccupied Aerial Systems (UAS) technology have provided biologists with a new tool to monitor wildlife populations (Gonzalez et al. 2016; Hodgson et al. 2016; Su et al. 2018). Waterfowl brood surveys, which have traditionally been conducted from the ground, can often be (1) time-consuming, (2) difficult with tall emergent vegetation, (3) have low detection probabilities, and (4) require experienced observers (Pagano and Arnold 2009). UAS in combination with thermal infrared (TIR) cameras have recently been used to conduct brood counts for waterfowl in cropland-dominated landscapes of the Prairie Pothole Region (Mitchell et al. 2023), with detection rates much higher compared to ground surveys (Bushaw et al. 2021).

Suisun Marsh is actively managed and preserved through the Suisun Marsh Habitat Management, Preservation, and Restoration Plan; a 30-year plan to protect and restore wetlands, ecological processes, and species (USBR 2013). Because Suisun Marsh is important for breeding waterfowl in California and is actively managed to support them, it is an ideal site for using emerging technologies to monitor local breeding populations.

Here, we used UAS technology to assess broods in wetland habitats. We used a blend of thermal detection and multi-spectral (5-band) imagery—in combination with previously collected Light Detection and Ranging (LiDAR) data—to map habitat characteristics within each surveyed unit to relate to our observed brood counts.

METHODS

Study Area

Suisun Marsh, California, USA (38°10’N, 121°58’W) is the largest contiguous brackish marsh in the United States (CVJV 2020). The brackish estuary comprises approximately 21,044 ha of publicly and privately managed wetlands, 2,428 ha of unmanaged tidal marsh, 12,141 ha of bays and sloughs, and 10,927 ha of upland grasslands (CVJV 2020). Privately managed wetland ponds are predominantly composed of waterfowl hunting clubs, and public wetlands are managed by Grizzly Island Wildlife Area. We conducted UAS brood surveys at seven different private waterfowl hunting clubs (hereafter clubs, 477 ha) within Suisun Marsh (Figure 1). All wetland units were flooded at the time of the survey. For clubs with multiple ponds separated by levees, we analyzed each pond as a separate wetland unit, resulting in a total of 17 discrete wetland units surveyed.

Brood Detection

We conducted UAS surveys between June 3-7, 2019 using a 3DR Solo platform (*https://www.3dr.com/)* equipped with a forward-looking infrared (FLIR) thermal camera (VUE Pro 640, 9mm, 30Hz; Teledyne FLIR, Wilsonville, Oregon) to detect broods across 17 discrete brood pond units within Suisun Marsh (Mackell et al. 2024) (Figure 2). We conducted thermal surveys at 30 m above ground level (AGL) with a flight speed of 7 m s-1 for optimal detection, and similar to methods outlined by Bushaw et al. (2021) and Dundas et al. (2021). We created survey transects using Mission Planner software (version 1.3.68, *https://ardupilot.org/planner*) with ground sampling distance overlap set to zero. We conducted surveys with a three-person team including the UAS operator, a data transcriber, and a screen monitor. The UAS operator was in charge of operating and maintaining a visual line of site with the UAS. The screen monitor would watch the live feed from the thermal camera and determine a hot spot, which would trigger the operator to pause the autonomous transect survey and manually fly the UAS lower to further inspect the hot spot. The data transcriber would record the encounter time, the encounter type (brood or false detection), the number of adult ducks, and the number of ducklings. After an encounter, the operator would resume autonomous flight on the transects. We began surveys after 09:00 to ensure optimal detection from a larger contrast in thermal signatures between target species and the background surface (sunrise 05:45). Survey end time was typically between 13:00 and 15:00 either because of increased wind speeds or battery limitations. Solar noon was approximately 13:08. We used encounter time, video feed, and flight logs from the solo platform to geo-rectify the location of each brood into NAVD88 UTM Zone 10 and check the data collected in the field.

Before the main UAS survey in Suisun Marsh, field staff received training in May 2019 to identify

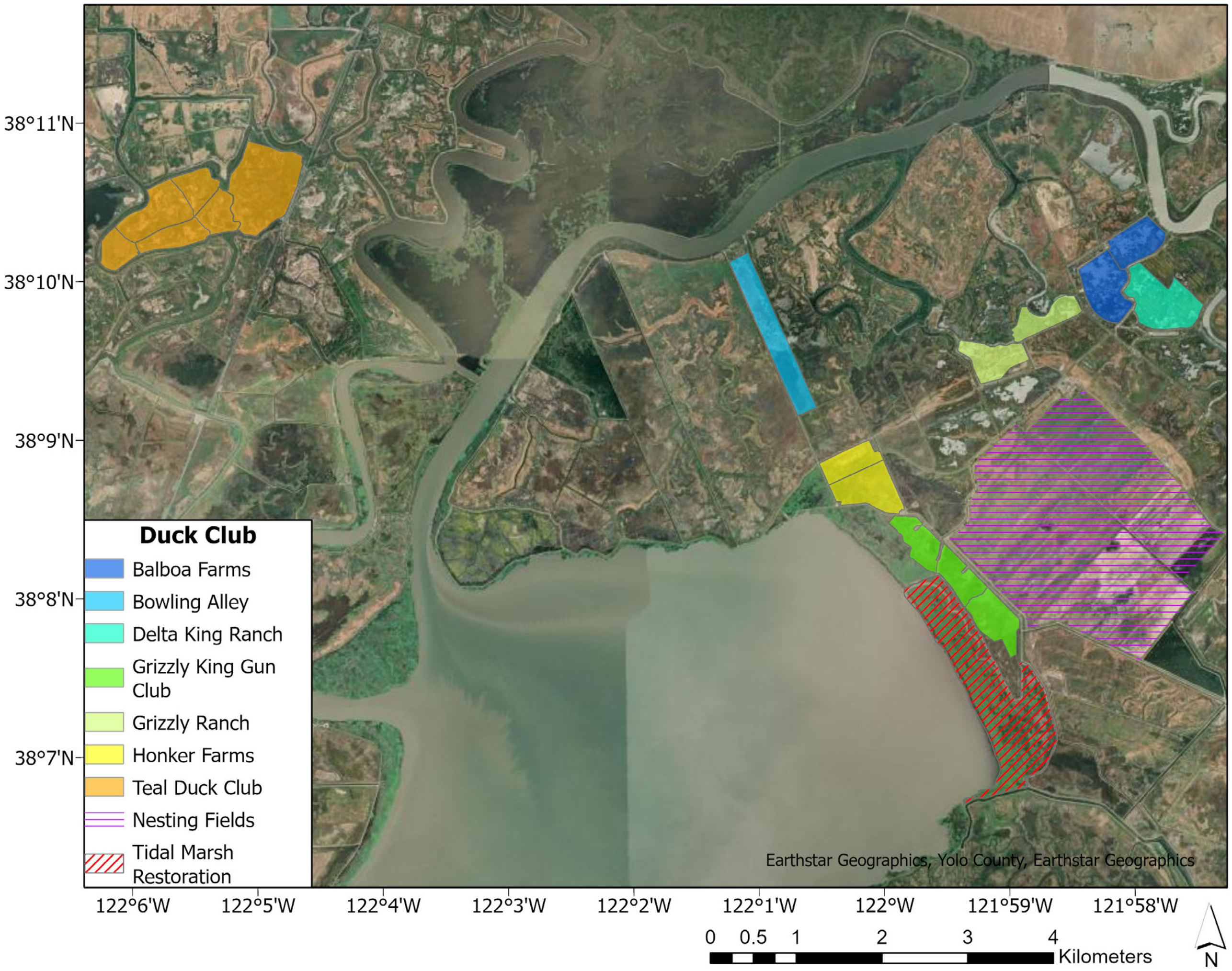
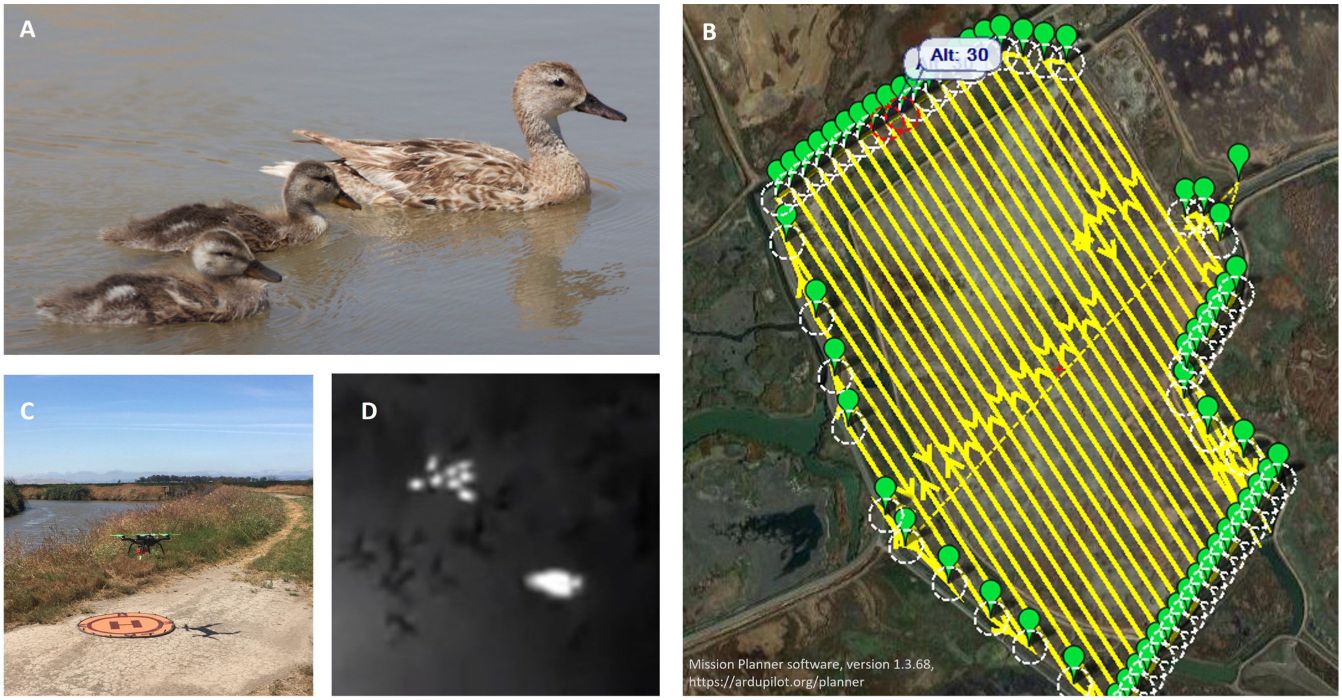


Figure 1 Seven privately owned duck clubs, consisting of 17 total discrete pond units, were surveyed for broods in Suisun Marsh of California from June 3–7, 2019. Surveys were conducted using an Unoccupied Aerial Vehicle (UAV) equipped with a thermal imaging sensor. Within Suisun Marsh, Grizzly Island Wildlife Area is managed for breeding waterfowl and has a large upland nesting unit (*purple shading*) near the ponds that we surveyed. Additionally, wetlands managed for waterfowl in Suisun Marsh are actively being converted to tidal marsh in efforts to restore tidal habitat. The area directly adjacent to the surveyed Grizzly King Gun Club (red shading) was converted to tidal marsh 4 months after we completed our brood surveys.

ducklings using thermal imaging. The purpose of the training was to familiarize the staff with the thermal signatures of marsh wildlife. During the training, they identified thermal signatures that resembled waterfowl. A technician would then walk into the wetland to locate the thermal signature. Once located, they would confirm the type of encounter, such as mammal, duck, duckling, or passerine.

Vegetation Mapping

After we conducted thermal surveys, we equipped the 3DR Solo platform with a multi-spectral sensor (MicaSense RedEdge-M; Micasense, Seattle, WA) to assess habitat within the 17 units. The multi-spectral surveys were conducted at 122 m AGL with a flight speed of 9 m s^{-1}, producing a 75% overlap, and transect spacing set for a 75% side lap to ensure a consistent data output. We conducted multi-spectral surveys between July 8 and 12, 2019, during a 4-hr window centered around solar noon. We post-



Mission Planner software, version 1.3.68, https://ardupilot.org/planner

Figure 2 (**A**) Gadwall (*Mareca strepera*) hen and ducklings; (**B**) UAS flight lines for survey (Balboa-2); (**C**) UAS equipment at study site; and (**D**) Thermal imagery from brood survey showing an adult hen (*right*) with her eight ducklings. *Black/grey* background is water and vegetation.

processed multi-spectral flight imagery using Agisoft Metashape software (version 1.7.5, *https://www.agisoft.com*) to produce an 8-cm horizontal resolution, 4-band orthoimagery layer. We then created a map with **three land-cover types**: Open Water, Barren Ground, and Vegetation. To do this, we used the 4-band orthoimagery, as well as a spectral index layer that represented the Normalized Difference Vegetation Index (NDVI). We conducted a supervised classification of the imagery using ArcGIS Pro (version 3.0.0, *https://www.arcgis.com/index.html*). To reduce the inter-class variability and produce a more accurate final map, training data included additional land-cover classes that were combined in the final map. In total, the training classes included three sub-classes for barren ground, one sub-class for open water, and four sub-classes for vegetation. However, we found that using sub-classes was not appropriate for subsequent models because of unequal distribution across wetland units and the inability to verify predicted occurrences at some locations.

Water Mapping and Habitat Types

We first visually mapped pond water extent by inspecting each pond using PlanetScope 3-m-resolution satellite imagery from the same week that we flew the brood flights (Image ©2019 Planet Labs PBC, *https://api.planet.com*). Using ArcGIS Pro (version 3.0.0), points along the water's edge that were visually identified were then intersected with LiDAR data (1-m resolution) that represented pond-bottom elevation from September of 2018 (Buffington et al. 2019). This allowed us to approximate the height of the water level along each ponds edge, which we then averaged (median) to estimate the water height for the entire pond. This method enabled us to use satellite imagery to identify water that was hidden under emergent vegetation during our visual inspection, and to determine the flooded area of wetlands within each unit.

We collected multi-spectral imagery several weeks after our thermal brood surveys, and some clubs had already begun to draw down water before we could map vegetation. Therefore, we used the water map derived from the LiDAR data

Table 1 Results from the UAS thermal brood and habitat imagery surveys. Coordinates of each unit are in NAD 1983 Universal Transverse Mercator zone 10.

Site	Easting	Northing	Survey date	Hectares (ha)	Number of broods	Number of ducklings	Hectares flooded	Proportion flooded	Open water (ha)	Barren (ha)	Flooded veg (ha)	Dry veg (ha)	Edge median (m)	Effective (ha)
Balboa-1	579195	4225489	6/3/2019	24.38	1	3	15.37	0.63	11.41	0.06	3.96	8.95	6.32	13.82
Balboa-2	587500	4222263	6/3/2019	33.35	23	187	26.54	0.80	19.77	0.10	6.77	6.71	8.72	23.58
Bowling Alley	590257	4224615	6/5/2019	48.20	6	34	37.40	0.78	31.95	0.51	5.45	10.29	18.38	14.91
Delta King	586375	4224072	6/5/2019	43.58	3	22	22.94	0.53	2.70	0.42	20.24	20.22	2.78	22.94
GrizzlyKing-1	590908	4224457	6/4/2019	20.35	7	75	14.95	0.73	7.72	0.31	7.23	5.09	6.73	14.32
GrizzlyKing-2	588966	4220743	6/4/2019	19.30	14	122	16.87	0.87	10.51	0.18	6.36	2.25	11.59	16.33
GrizzlyKing-3	590615	4225141	6/4/2019	26.34	9	65	18.96	0.72	15.23	0.47	3.73	6.91	8.89	15.76
GrizzlyRanch-1	579663	4225783	6/5/2019	20.04	0	0	11.62	0.58	10.30	0.47	1.32	7.94	5.74	8.89
GrizzlyRanch-2	580431	4225793	6/5/2019	24.74	0	0	13.38	0.54	10.39	1.31	3.00	10.05	7.05	10.99
HonkerFarms-1	588072	4221658	6/5/2019	19.09	1	2	14.94	0.78	6.84	0.01	8.10	4.13	10.26	14.42
HonkerFarms-2	588549	4221246	6/5/2019	31.18	14	89	26.36	0.85	18.55	0.01	7.82	4.81	8.40	24.57
TealClub-1	589552	4224263	6/6/2019	18.83	1	9	12.59	0.67	8.17	0.13	4.41	6.11	14.88	12.47
TealClub-2	588940	4223786	6/7/2019	65.75	7	56	43.57	0.66	15.32	0.15	28.26	22.03	13.07	42.53
TealClub-3	587275	4222581	6/7/2019	33.94	10	76	23.45	0.69	15.08	0.56	8.37	9.93	10.77	22.74
TealClub-4	578726	4225048	6/7/2019	16.69	12	68	11.87	0.71	8.07	0.41	3.79	4.41	10.67	9.16
TealClub-5	579399	4225209	6/7/2019	16.81	5	19	12.50	0.74	7.40	0.07	5.10	4.24	20.86	10.64
TealClub-6	579908	4225476	6/7/2019	14.49	0	0	8.20	0.57	1.94	0.13	6.26	6.15	5.05	8.20
			Totals	**477.07**	**113**	**827**	**331.52**	**0.70**	**201.35**	**5.32**	**130.16**	**140.23**	**170.16**	**286.27**

in combination with the supervised classification results to create four habitat types that accurately reflected water levels at the time of the brood surveys. These **four habitat types** were (1) Open Water, (2) Barren, (3) Flooded Vegetation, and (4) Dry Vegetation, which were then used as explanatory variables in our brood-abundance models (Table 1, Figure 3).

Edge and Effective Habitat

We calculated the area of Open Water, Barren, Flooded Vegetation, and Dry Vegetation habitat types and estimated the amount of edge and effective habitat within each club unit in our brood analysis (Table 1). To estimate the amount of habitat present along the water's edge, which we define as **edge habitat**, we created a 1-m raster grid across the water's extent in each of the 17 club units. Next, we calculated the median distance from each raster cell to the water's edge for each unit. This provided us with an estimate of the amount of edge habitat present in each unit. For example, a larger median distance to the edge would indicate less edge habitat. This method also enabled us to account for the complex structure of the surveyed units, which included irregular shapes, patches, and islands within ponds. Additionally, broods in our system were not observed to use dry habitat or large swaths of open water, and were found near vegetative cover. We wanted to estimate the area of habitat that was of functional use to broods, which we defined as effective habitat. Effective habitat was calculated by summarizing the 95th-percentile Euclidean distance that all broods were from any vegetated cover identified in our supervised classification. We then calculated the area of flooded habitat for each club unit that was within two times that distance as a buffer for areas that may be important to broods and to account for the ability of broods to move between patches (Table 1, Figure 3).

Brood Abundance Model

We tested whether brood abundance—which we define as the total number of broods observed

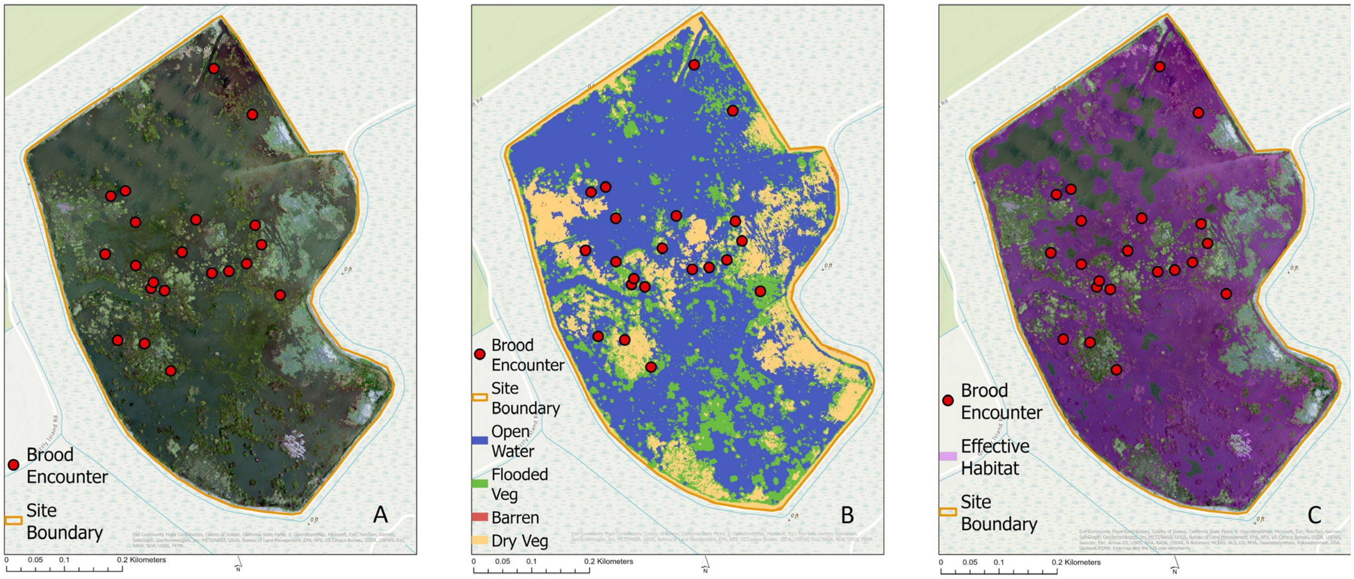


Figure 3 (**A**) The multi-spectral orthoimagery (5-band, 8-cm-resolution) collected from the drone flight at the duck club Balboa-2. Brood encounters are represented by the *red dots* on each map. (**B**) The imagery from the drone flight was used in a supervised classification process to classify four habitat types: Open Water (*blue*), Flooded Vegetation (*green*), Dry Vegetation (*yellow*), and Barren (*red*). (**C**) Effective habitat (*purple*) was defined as the flooded area within 8.43 m of vegetation (2x the 95th percentile distance that all broods were located from vegetation).

in a unit—was influenced by wetland habitat extent, wetland habitat composition, and wetland configuration. Our results were modeled using a negative binomial regression with a log link to account for over-dispersion, which may occur with a low sample size (17 units) and the absence of brood detections at three sites. Since not all habitat types (e.g., Bare Ground, Flooded Vegetation, etc.) provide equal resource value to broods, thematic accuracy (Mas et al. 2014) of our definition of habitat was crucial. Therefore, using three alternative metrics, we developed an initial model that described functional relationships between brood abundance and extent of habitat defined. These three habitat extent metrics included total area of all land-cover types (e.g., the entire wetland unit), flooded extent of the wetland unit (flooded vegetation and open water), and the area of effective habitat (flooded vegetation and open water near cover, see "Edge and Effective Habitat" earlier) within each wetland unit. Each metric was modeled independently and in conjunction with the proportion of the unit flooded, which itself was modeled as a linear additive relationship with brood count and with a non-linear quadratic relationship with brood count (which would suggest that peak brood counts depend on some level of flooded/non-flooded heterogeneity). These efforts resulted in **nine *a priori* models** that described the functional relationships between brood abundance and wetland quantity and condition, but that did not include specific habitat composition or configuration metrics (Table 2). Models were compared using Akaike's Information Criterion corrected for small sample sizes (AICc) (Burnham et al. 2002). The best performing of these models represents the simplest functional relationship between brood abundance and habitat extent, which we refer to as our **functional null model.**

Upon determining the best functional relationship between brood abundance and habitat extent, we ran a second suite of models that combined the functional null model with several wetland habitat configuration or composition measures, including: area of flooded vegetation, area of dry vegetation, area of open water, and median distance to pond edge within the wetland unit (Table 3). Area of barren habitat was not included in our models because of its extremely

Table 2 Functional null models ranked by AICc. The best functional null model relating broods:area used effective habitat as our area metric and included the proportion of the unit that was flooded as a predictor for the number of broods found. All models were run as negative binomial regressions to account for overdispersion.

Model name	K	AICc	Delta_AICc	ModelLik	AICcWt	LogLik	Cum.Wt
Effective habitat, proportion flooded	4	97.981	0.000	1.000	0.354	–43.324	0.354
Total area, proportion flooded	4	98.770	0.789	0.674	0.239	–43.718	0.593
Area flooded, proportion flooded	4	99.148	1.167	0.558	0.198	–43.907	0.791
Effective habitat, proportion flooded (quadratic)	5	100.542	2.561	0.278	0.098	–42.544	0.889
Total area, proportion flooded (quadratic)	5	101.710	3.729	0.155	0.055	–43.128	0.944
Area flooded, proportion flooded (quadratic)	5	102.218	4.237	0.120	0.043	–43.382	0.987
Effective habitat	3	106.238	8.257	0.016	0.006	–49.196	0.992
Area flooded	3	106.361	8.379	0.015	0.005	–49.257	0.998
Total area	3	108.155	10.173	0.006	0.002	–50.154	1.000

Table 3 Model results investigating the relationship between number of broods detected and our four habitat characteristics (area of flooded vegetation, area of dry vegetation, open water, and edge habitat). Our functional null model (*top model* from Table 2) was used as the base model for all other models, with each habitat characteristic being added independently. Model results were ranked by AICc with our functional null model ranked as the best. All models were run as negative binomial regressions to account for overdispersion.

Model name	K	AICc	Delta_AICc	ModelLik	AICcWt	LogLik	Cum.Wt
Functional null	4	97.981	0.000	1.000	0.653	–43.324	0.653
Edge habitat	5	101.913	3.931	0.140	0.091	–43.229	0.744
Flooded vegetation	5	101.996	4.015	0.134	0.088	–43.271	0.832
Dry vegetation	5	102.052	4.071	0.131	0.085	–43.299	0.917
Open water	5	102.101	4.120	0.127	0.083	–43.323	1.000

low prevalence that would disproportionately influence and skew our results (Table 1). These models were also ranked using AICc. All models were run using program R (Version 4.2.2) (R Core Team 2022).

RESULTS

Brood Surveys

We flew UAS surveys over 477 ha. We observed rabbits and passerines during surveys but they were easily distinguishable from ducks and ducklings. Adult ducks had clear oval shapes and were usually located near smaller, brighter round ovals. Jerky swimming motions were usually observed making them distinguishable from other avian species. During the surveys we encountered egrets, blackbirds, and small waterbirds. Overall, we had 362 avian encounters during our surveys. Of those, 223 encounters were either a single adult duck or pair of adult ducks with no observed ducklings. We identified twenty encounters as waterbirds (which included egrets, pelicans, and shorebirds) three as blackbirds, and were unable to identify three birds. We observed thermal signatures an additional 220 times, but—during flight and upon closer inspection—the UAS operator and screen monitor determined they were not wildlife but instead signatures of vegetation and duck decoys that had apparently been heated by the sun.

In total, we were able to identify 113 individual broods comprising 827 ducklings (Table 1, Figure 4). The number of broods found in each wetland unit ranged from 0 to 23, with an arithmetic mean of 6.45 (95% CI ±3.32). The number of ducklings found per unit ranged from 0 to 187, with a mean of 48.65 (95% CI ±26.66). We identified broods in 14 of the 17 units surveyed.

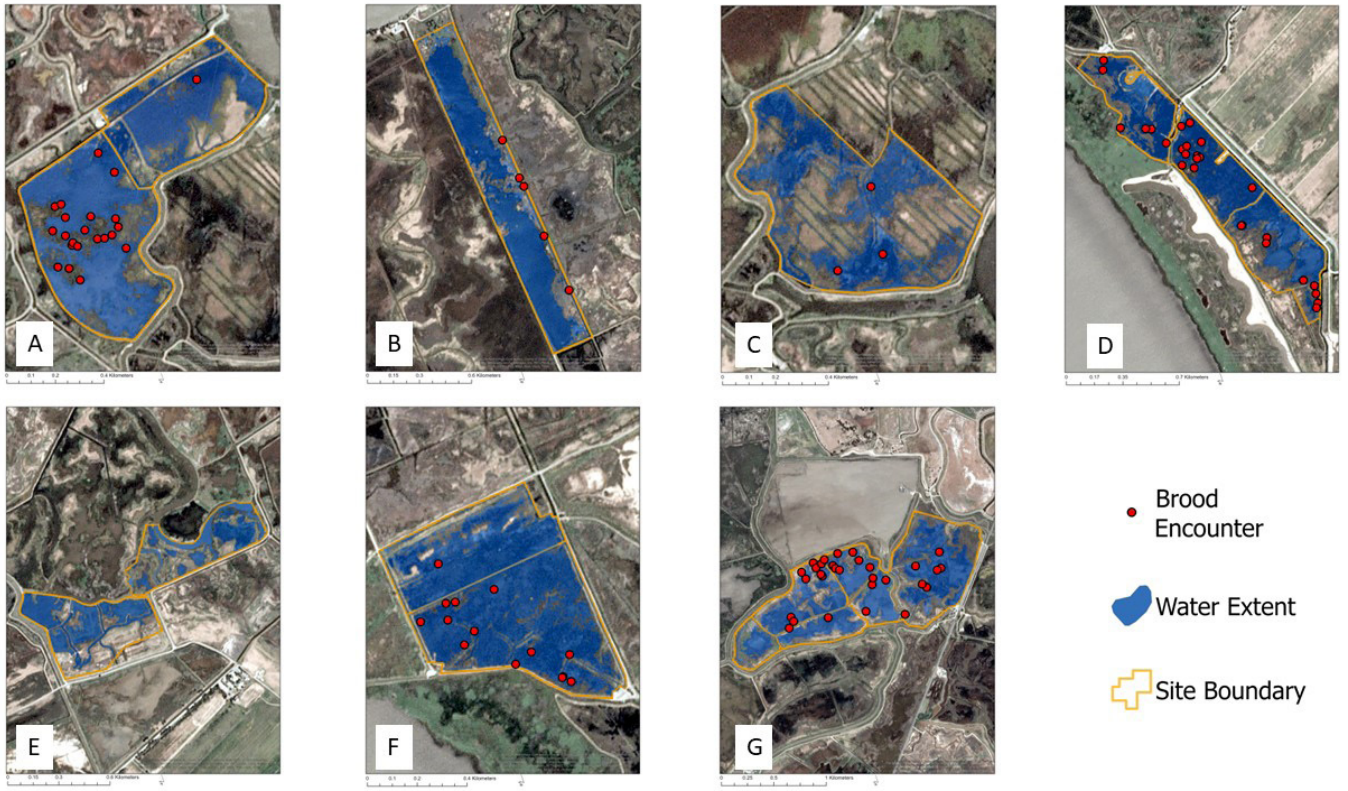


Figure 4 Broods observed within each duck hunting club. (**A**) Balboa. (**B**) Bowling Alley. (**C**) Delta King Ranch. (**D**) Grizzly King Gun Club. (**E**) Grizzly Ranch. (**F**) Honker Farms. (**G**) Teal Duck Club. The PlanetScope 3-m resolution satellite imagery in each map is from the same week as the drone flight, and was used to help identify the water extent represented in *blue* (Image © 2019 Planet Labs PBC).

Only Grizzly Ranch-1, Grizzly Ranch-2, and Teal Club-6 had no broods identified within their boundaries. Balboa-2 had the most broods (23) and the most ducklings found among all units (187) (Table 1). The largest brood size that we observed was 25 ducklings with one adult. The smallest brood size observed was one duckling with an adult (Appendix A).

Habitat Classification

We mapped water extent for each unit. Of the 477 ha of area surveyed, we identified approximately 332 ha as flooded at the time of our thermal surveys. Across all 17 units, 130 ha of the flooded area was vegetated while 201 ha was open water (Table 1). The proportion of each unit that was flooded ranged from 0.53 (Delta King) to 0.87 (Grizzly King-2), with a mean of 0.70 (95% CI ± 0.05). Flooded vegetation ranged from 1.32 ha (Grizzly Ranch-1) to 28.26 ha (Teal Club-2), with a mean area of 7.65 ha (95% CI ± 3.44 ha). Teal Club-6 had the lowest amount of open water (1.94 ha) while Bowling Alley had by far the largest amount of open water (31.95 ha), which was 12.18 ha more than the unit with the next-largest amount of open water (Balboa-2). Average open water habitat across all clubs was 11.84 ha (95% CI ± 3.69 ha). Dry vegetation ranged from 2.25 ha (Grizzly King-2) to 22.03 ha (Teal Club-2), with a mean of 8.25 ha (95% CI ± 2.77 ha). Barren habitat (devoid of vegetation and water) was the scarcest habitat type across all units, with an average of 0.32 ha (95% CI ± 0.164 ha). Median distance from the water's edge within flooded habitat ranged from 2.78 m (Delta King) to 20.86 m (Teal Club-5), with an average of 10.01 m (95% CI ± 2.43 m). We found that 95% of duckling locations occurred within 4.21 m of mapped vegetation extents among all wetland units. Therefore, we defined the **effective region where a brood may be found** as flooded habitat within 8.43 meters of vegetation identified in our supervised classification. The amount of effective habitat ranged from 8.2 ha (Teal Club-6) to 42.53 ha (Teal Club-2), with a mean area of 16.84 ha (95% CI ± 4.36).

Brood Abundance in Relationship to Habitat Characteristics

The most parsimonious model that related brood abundance with wetland habitat area and wetland condition—our functional null model—included the extent of effective wetland habitat and a linear relationship with the proportion of wetland unit that was flooded (Table 2). Effective wetland extent consistently, but not significantly, out-performed wetland unit size and total flooded area among comparable model formulations. The proportion of unit flooded was most effectively modeled as a linear predictor of brood size, which out-performed both a quadratic relationship and no modeled relationship between brood count and the proportion of unit flooded (Table 2). Each of the top three candidate null models (Table 2) contained a different habitat extent metric and included the same linear relationship with the proportion of the unit flooded— and each model had performed similarly (ΔAICc < 2). Despite similar performance, we retained only the top-performing model to use as our functional null. We then used this model to evaluate the effects of habitat composition and configuration on brood abundance. However, none of the wetland habitat composition or configuration metrics (area of Flooded Vegetation, Dry Vegetation, Open Water, or Edge Habitat) significantly improved the functional null model's ability to estimate brood abundance (Table 3, Table 4).

Table 4 Parameter estimates and summary statistics of the best model, which was also our functional null model. The dependent variable (number of broods) was best predicted by the extent of effective habitat combined with the proportion of the wetland unit that was flooded.

	Estimate	Std. Error	z value	p
Intercept	– 4.94	1.49	– 3.31	0.001
Effective habitat	0.04	0.02	2.00	0.045
Proportion flooded	8.28	1.99	4.16	< 0.001

DISCUSSION

Informative Habitat Characteristics

Remote sensing can provide wildlife managers with spatial and temporal habitat metrics to better understand their systems and make data-driven decisions. For example, remote sensing has been used to select and monitor wetland restoration sites (Klemas 2013), to understand how wetland loss can affect waterbird migration (Donnelly et al. 2022), and to monitor non-native species (Alvarez–Taboada et al. 2017). Our methods leveraged satellite, LiDAR, and UAS imagery to classify wetland characteristics of available brood habitat to relate to brood abundance.

Our top-performing models showed a significant relationship between the number of broods detected, the area of effective wetland habitat, and the proportion of the unit flooded. These could be important variables to track over time for brood abundance and for selecting future wetland sites to survey. Hemi-marsh has been shown to benefit breeding dabbling duck pair numbers and species diversity (Masto et al. 2022). Our results indicate a relationship between effective habitat and brood abundance, highlighting that hemi-marsh may also be an important habitat component of brood pond management. Monitoring additional wetland habitat characteristics in conjunction with UAS brood flights could provide further insight into breeding success and habitat-selection patterns. Incorporating additional vegetation measurements (species composition, plant structure), salinity, and water depth into surveys may help identify habitat features that promote or diminish brood production. Additionally, classifying broods down to the species level could help account for species-specific differences in functional response to habitat conditions that we were not able to capture because of our equipment restraints (our UAS was only able to carry one camera payload at a time). Such efforts may be particularly beneficial where surveys can reference habitat changes related to wetland management practices and on-going tidal marsh conversion efforts.

Emerging Technologies

Ecological monitoring of wildlife populations and their habitats can improve wildlife management. Brood surveys are a traditional approach to estimating waterfowl productivity and have been used for decades (Hammond 1970; Brown et al. 1993). However, concerns about duckling estimates derived from visual field counts have been raised due to difficulties in detecting ducklings within emergent vegetation in wetlands (Pagano and Arnold 2009). Therefore, wildlife managers are increasingly interested in exploring other survey options, specifically UAS. A growing body of literature highlights the increasing use of UAS; for example, a recent study was able to demonstrate that brood detection in wetlands increased by almost 50% when UAS rather than ground surveys were used. (Bushaw et al. 2021). UAS and TIR cameras have also been used to detect white-tailed deer (Chrétien et al. 2016), and Hodgson et al. (2018) suggest that UAS monitoring applications could assist with fine-scale population fluctuations in seabird colonies.

CONCLUSION

Unoccupied aerial system reconnaissance that incorporates simultaneous thermal surveys and multi-spectral habitat quantification provides a methodology that was effective across multiple properties with varying habitat types (e.g., amount of Open Water vs. Flooded Vegetation) in Suisun Marsh (Table 1). This method proved to be a possible economical option that could be completed within a relative short period of time. Three people surveyed seven duck clubs and approximately 477 ha over the course of 5 days, demonstrating the efficiency of this method both in terms of time and staff. A total of 113 broods were detected, comprising 827 ducklings. The largest brood contained 25 ducklings and was likely the result of brood amalgamation (Eadie et al. 1988). Broods were often found near the water's edge and in vegetated areas that would be hard to detect via ground surveys (Figure 4). Additionally, the UAS's capacity to carry multi-spectral imagery sensors allowed for high-resolution classification of vegetation and habitat indices to be used in combination with broods counts.

Management Decision-Making

Management decision-making depends on accurate and timely data to inform actions and regulations, and the California Waterfowl Association and the California Department of Fish and Wildlife are in the process of creating/restoring approximately 50 ha of reverse cycle ponds on Grizzly Island Wildlife Area (2023 videoconference between R. Eddings and D. Mackell, unreferenced, see "Notes"). These ponds are directly adjacent to the main nesting uplands on the wildlife area and are being restored with the explicit intention of providing brood habitat to waterfowl in the spring and early summer. UAS surveys could help monitor the success of this project and could assist wildlife managers looking to adaptively manage these ponds to best support broods. The information gained from annual surveys of these restoration areas may also help inform future breeding habitat management plans and identify additional sites of high conservation value for restoration in the region.

Tidal marsh habitat in Suisun Marsh is actively being restored through the conversion of managed wetlands. The goal is to convert 5,000 to 7,000 acres of managed wetlands into tidal marsh to assist in the recovery of special-status species (e.g., Salt Marsh Harvest Mouse, Delta Smelt, salmonids) and increase resiliency to sea level rise (USBR 2013). Utilizing UAS technology could be an opportunity to measure how the loss of these managed wetlands affects waterfowl reproductive output in the region. Specifically, ponds could be surveyed for broods before and after tidal marsh conversion to quantify shifts in brood occupancy and abundance. Since the completion of our study, the duck club directly adjacent to one of our surveyed sites has been converted to tidal marsh (WES 2020) (Figure 1). We found 30 broods and 262 ducklings at that site; the effect of the converted habitat to breeding waterfowl in the area is unknown. Adult waterfowl species that breed in Suisun Marsh have already been shown to highly select managed wetlands over tidal marsh (Casazza et al. 2021). Conversion to tidal marsh may also affect habitat suitability for ducklings; for example, by increasing salinity, altering pond depth, and changing the unit's vegetation composition. Salinity levels have been shown to be high enough to impair duckling growth and survival in Suisun Marsh (Schacter et al. 2021). Monitoring of these changes as potential sources of habitat loss to breeding waterfowl in Suisun Marsh fall within the monitoring guidelines outlined in the Suisun Marsh Management Plan and would inform their multi-species adaptive management goals (USBR 2013).

Application to the San Francisco Bay-Delta

Lastly, UAS brood surveys can complement the current model of monitoring breeding waterfowl populations in Suisun Marsh (i.e., Breeding Population Survey), allowing for fine-scale and targeted observations (e.g., refuge pond, private hunting club) that focus on post-nesting success. Water availability in Suisun can significantly decrease after the Breeding Population Survey is conducted (Schacter et al. 2021). This decrease in water availability leading into the brood-rearing period could negatively affect breeding success, which survey results may not accurately reflect. Utilizing UAS platforms, TIR cameras, and multi-spectral sensors can help managers better understand breeding dynamics within the marsh and thus make more informed conservation decisions. While this study provides evidence to support the efficacy of UAS to survey broods in Suisun Marsh, further investigations that include additional habitat and water-quality measures—as well as the classification of species and brood age—could be useful to guiding management moving forward. Future studies could also include paired UAS surveys with ground brood surveys to test the viability for more robust population estimates.

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NOTES

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