Assessing superimposition of listed tule fall Chinook salmon redds using aerial and ground surveys on the White Salmon River, Washington

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Abstract

Upriver bright (URB) fall Chinook salmon reared and released from the Little White Salmon and Willard National Fish Hatcheries are known to stray into the White Salmon River. Interactions between hatchery-origin URB strays and ESA-listed tule fall Chinook salmon are believed to lead to a loss in productivity of the native tule population through hybridization and redd superimposition. Tule fall Chinook salmon generally spawn earlier in the fall (September – October), which puts their redds at risk to superimposition by URB fall Chinook salmon that typically spawn later (late October – November). Superimposition may result in egg displacement and reduce egg-to-fry survival leading to a loss in productivity of the tule fall Chinook population. An initial pilot feasibility study conducted in the fall (September – November) of 2022 found a high incidence (71 percent) of tule redds superimposed by URBs. In 2023, we developed this initial study further by supplementing weekly ground surveys with aerial surveys using an unmanned aerial vehicle (UAV; i.e., drone) to provide high-resolution imagery of spawning grounds. Ground surveys followed the same methodology as employed in 2022. Redd locations were documented weekly using ArcGIS Field Maps and an Arrow RTK GNSS Receiver resulting in centimeter-level location accuracy. Four independent aerial observers reviewed and identified redds from weekly imagery. The degree of overlap among redds (i.e., > 50 percent overlap) was used to distinguish superimposed redds. The total number of tule redds and percent superimposed were compared among methodologies. The ground crew had 1.5 times higher tule redd counts than averaged aerial observers counts, though inter-observer variability was high (CV = 80 – 98 percent) for aerial surveys. Ground count variability was not measured because there was only one ground crew. Overall, the percent of tule redds superimposed was substantial (66 percent estimate by aerial surveys – 94 percent estimate by ground surveys) with greater counts from ground surveys when the same areas were compared. Herein, we present a comparison of results from both methodologies, evaluate pros and cons, and suggest potential changes to the methodology of surveys in 2024.

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INTRODUCTION

A pilot study conducted on the White Salmon River in 2022 found a high proportion (71 percent) of tule fall Chinook salmon redds were superimposed by later spawning upriver bright (URB) fall Chinook salmon (Baker and Hand 2023). These results draw attention to the potential impacts of URBs (both hatchery and natural origin) on the ESA-listed tule population. The pilot study focused on spawning locations within a section of the first river mile of the White Salmon River, where the majority of tule and URB spawning occurs (Olk and Dammerman 2022). Expanding the area surveyed to encompass larger sections of the river would be challenging using the intensive survey methods to document superimposition (i.e., weekly mapping of individual redds). Additionally, deep water and swift currents in some river sections prevented the ground crew from accessing all spawning habitat. Safety is always a concern when dealing with intermittent high flows on the White Salmon River. In addition to these concerns, ground surveys could be invasive at times, disturbing fish away from guarding redds and/or potentially damaging redds during data collection. Aerial surveys may have several advantages over ground based surveys in addressing these concerns. For example, aerial images taken from an unmanned aerial vehicle (UAV) (i.e., drone) of spawning grounds could provide a less invasive approach with lower inherent risk and allow images to be archived for future use.

Several recent studies using UAVs have been successful in identifying salmonid redds (Groves et al. 2016; Roncoroni and Lane 2019; Harrison et al. 2020; Auerbach and Fremier 2022). One of these studies directly compared counts of summer Chinook salmon redds from UAV-based images with ground-based counts in the Wenatchee River (WA, USA) (Auerbach and Fremier 2022). The study found that redd counts using drones was an effective method, particularly in high-density spawning locations, though there was large variability among aerial counters due to inherent uncertainties in redd identification (e.g., hydraulic features, test redds, superimposition). Counts of redds from UAV-based images were consistently higher than ground counts, which the authors suggested was due, in part, to the improved ability of repeat aerial photography for distinguishing superimposed redds (Auerbach and Fremier 2022). The study, however, did not necessarily conclude that aerial counts were more accurate than ground counts, stating that additional validation datasets were needed for making this assessment (Auerbach and Fremier 2022). We are not aware of any studies that specifically compare redd superimposition estimates using ground and aerial surveys.

In this study we supplemented weekly ground surveys with concurrent aerial surveys using a UAV to provide high-resolution imagery of spawning grounds. We compared counts of redd superimposition among survey methods and evaluated their advantages and disadvantages. Comparisons were made for the entire area sampled using each method, as well as a smaller area that was comparable to that accessible by the ground crew. Results from this study will be used to make informed decisions and potential changes to the methodology of surveys in 2024.

Figure 1. Location of reaches surveyed on the White Salmon River from September – November 2023.

STUDY AREA

The White Salmon River is a 5th order stream with a basin of approximately 1,000 km^2 (386 mile^2) that enters the lower Columbia River at RKM 269 (RM 168) in Washington State. The river originates from Mount Adams in the Cascade Mountain Range and flows south 72 km (45 miles) before entering the Columbia River at Underwood, Washington. This study focused on spawning locations within the first river mile of the White Salmon River (Figure 1). Three survey reaches were selected to monitor the distribution of spawning tule fall Chinook covering an area of approximately 25,643 m^2 and 405 m of the river (Table 1). Reaches surveyed ranged from approximately 115 to 160 m in length with areas of 7,006 to 9,570 m^2. Two side channel reaches that were surveyed during the pilot study in 2022 were found to be unsuitable for spawning in 2023 due to shallow conditions with low flows. Thus, all three reaches surveyed in 2023 were main sections of the river above riffles (Figure 1). These areas of the White Salmon River had consistently high densities of spawning fish observed in past WDFW spawning ground surveys (Olk and Dammerman 2022) (Figure 2). The entire area of each reach was surveyed during aerial missions, while only some of the area was accessible to ground surveys due to deep water and swift current in some sections.

Table 1. Length and area of stream reaches surveyed in 2023.

Reach ID	General Location	Length of Reach (m)	Area of Reach* (m^2)
1	Upstream reach	160	9,570
2	Middle reach	130	7,006
3	Downstream reach	115	9,067
	Total	405	25,643

* Areas represent the total extent of area surveyed for each reach during aerial missions. The amount of area surveyed for each reach during ground surveys was less due to water depth and swift current.

METHODS

This study was conducted in the fall of 2023 focusing on spawning locations within the first river mile of the White Salmon River. Surveys were conducted throughout the spawning season (September – November) with varying flow, water level, turbidity, and weather conditions. Three survey reaches located upstream of the first series of riffles at RM 0.4 to RM 0.75 were selected to monitor the distribution of spawning tule fall Chinook salmon (Figure 1). The methodology described in the section below for ground surveys generally followed the methods employed in 2022 (Baker and Hand 2023). Initially, aerial surveys were completed on the same day as ground surveys to ensure direct comparisons. However, as redd densities increased in October it became more difficult to complete both ground and aerial surveys on the same day. Aerial surveys in October and November were typically flown 1-3 days following ground surveys.

Ground Surveys

A team of two to three biologists completed surveys weekly by walking upstream throughout each designated reach to collect data on the location of tule fall Chinook salmon redds. There was one biologist who was the same individual and present for all ground surveys. Starting with the early tule fall Chinook salmon spawning migration (i.e., week of September 4) and continuing through the fall (i.e., week of October 2), the crew completed surveys each week to identify tule redds[1]. During high spawning activity (e.g., late September and October), surveys were sometimes increased to twice a week as needed to help delineate additional redds. Tule and URB fall Chinook salmon were distinguished by maturation characteristics; tules exhibit advanced maturation and darkened skin at freshwater entry versus URB fall Chinook salmon, which have brighter skin at freshwater entry and mature 1–3 months after freshwater entry (Myers et al. 2006). Due to the similarity in appearance of tule and URB fall Chinook salmon it was often difficult to visually determine the identity of spawners. Due to the difficulties with identification, a cut-off date in early October (i.e., week of October 2) was used for surveys to ensure only redds of tule spawners were assessed for superimposition. This cut-off date corresponds to one and a half to three weeks before URBs were first observed during past WDFW spawning ground surveys[2] (Figure 2).

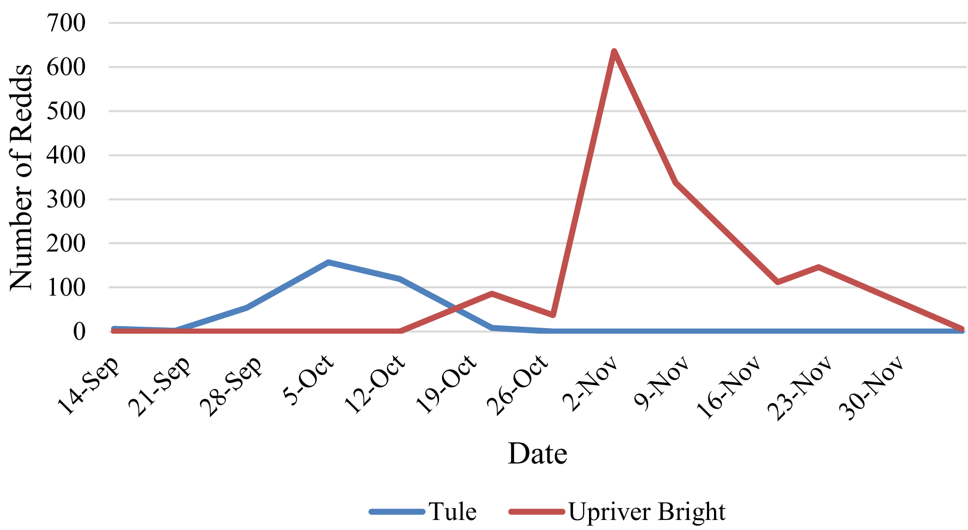

Figure 2. The number of fall Chinook salmon redds observed from the mouth of the White Salmon River to RM 1.44 during WDFW spawning ground surveys in 2021. Unpublished raw data provided by Elise

[1] Based on WDFW spawning ground surveys from 2015-2021, tule fall Chinook salmon spawners were first observed within the lower 1.44 RM of the White Salmon River between September 2 and October 3 (median date of first observation September 17), and were recorded through late October (i.e., October 21 through October 31).
[2] Based on WDFW spawning ground surveys from 2018-2021, URB fall Chinook spawners were first observed in middle to late October (October 19 through October 31).

Ground Survey Identification of Tule Redds

Tule fall Chinook salmon redds were identified by wading upstream throughout each designated survey reach. The gravel from recently dug redds appeared lighter colored and less uniformly oriented than the surrounding undisturbed gravel. All mature redds consisting of a pit (i.e., depression) on the upstream end and a tailspill of excavated gravels on the downstream end were identified (Burner 1951). Incomplete or test redds were noted but not counted as new redds until a clearly defined pit and tailspill was observed during subsequent surveys. Attention was taken to distinguish redds from areas of general scouring associated with high flows and large woody debris. Upon encountering a mature redd, surveyors identified the locations of the pit and tailspill area. If possible, pictures were taken of the redd looking downstream, including any landmarks on nearby banks to help identify the redd in subsequent surveys. The location of the redd was marked by taking a GPS point at the upstream end of the tailspill consisting of excavated gravels covering incubating eggs (i.e., egg pocket). Redd locations and associated GPS coordinates were recorded using a tablet computer with ArcGIS Field Maps and an Arrow RTK GNSS Receiver resulting in centimeter-level location accuracy. A polygon was created around clearly defined redds by walking around the outside perimeter of the redd. The boundary of the entire excavated portion of the redd back to the highest point of the tailspill was recorded. The downstream end of the tailspill was not included, as this area typically consists of excavated fine material not covering eggs and can sometimes have an elongated shape due to river currents carrying fines further downstream. In some cases, another polygon was created around the boundary of the redd during subsequent surveys to document the progression and expansion of the redd further upstream. In high-density spawning areas where redd boundaries overlapped, the total dimensional area of redds were recorded by walking around the entire border of the area with the disturbed substrate. A GPS point was also taken at the upstream end of individual tailspills within the disturbed area to document individual redds.

Additional data were recorded for each redd using a tablet computer with ArcGIS Field Maps including: a unique identification number for each redd observed, date, time, field crew, fish species, redd age (e.g., new redd, still present, still present but not measurable, no longer present, poor condition [cannot measure]), superimposed (no/partial/yes), disturbance (none/minor/major), fish presence on the redd (no/yes), fish sex (male/female/unknown), spawning behavior observed (pre-spawning/spawning/post-spawning), and general comments. River discharge was obtained from the USGS stream gage 14123500 located upstream on the White Salmon River at RM 1.9. Two HOBO Pendant MX data loggers recorded water temperatures at locations within the middle and downstream reaches. Data loggers were suspended in the water column at each location and recorded temperatures at one-minute intervals from September 8 through November 21.

Ground Survey Documentation of Superimposition

To document superimposition, tule redds identified during the initial survey period were monitored throughout the URB fall Chinook salmon spawning run (i.e., week of October 9 through week of November 20). Determination of redd superimposition was supported by field observations of identified tule redds that were excavated on top of by a URB fall Chinook salmon, including documenting fish presence and observations of digging or guarding of the new superimposed redd. When a new redd was observed near a previously documented tule redd, GPS coordinates and redd polygon boundaries, along with associated pictures of the tule redd, were used to assess the degree of overlap. Often a new GPS point and polygon boundary was created for the URB redd to assist in assessing overlap. Observations of tule redd alteration were noted in relation to the degree of overlap of redd boundaries and disturbance. A 0–2 rating system was used to classify the degree of overlap and disturbance to the tule redd and to characterize the level of superimposition observed. If there was no overlap of redds and no disturbance observed, the score was 0. Redds with less than 50 percent overlap and minor structural disturbances observed were scored 1. Redds severely altered with greater than 50 percent overlap were scored 2. Redds with scores of 2 were identified as superimposed, meaning that a significant overlap of redds had occurred coupled with substantial scouring and deposition to the point where the original tule redd perimeter and shape were unrecognizable. Field observations supported by GPS coordinates and boundaries of tule redds recorded with ArcGIS Field Maps and an Arrow RTK GNSS Receiver (i.e., centimeter-level location accuracy) were used to make determinations on whether the construction of the new redd superimposed a previously documented tule redd.

Unmanned Aerial Vehicle (UAV) Surveys

Ground surveys were supplemented with weekly aerial surveys throughout the spawning season using a UAV to provide high resolution georeferenced imagery of spawning grounds. Attempts were made to fly aerial missions on the same day as ground surveys, though this was not always feasible due to weather conditions and time constraints. Weather conditions were evaluated prior to UAV missions to determine feasibility. If a flight mission was canceled for any reason it was attempted on the following two days. Thus, aerial surveys were sometimes completed on different days each week depending on conditions. Aerial surveys of the upstream reach in September only covered a partial area of the survey reach. As a result, flight plans were modified starting with the October 3 survey to provide complete coverage of the upstream survey reach. The following survey reaches were lacking adequate aerial images to construct orthomosaics for specific dates: upstream reach (September 5, 12, 19, 29), middle reach (September 29, November 9), and downstream reach (September 5). A Parrot Anafi aircraft was used for all aerial missions containing a 21 megapixel camera with 4K resolution, 180º gimbal tilt, 3-axis hybrid image stabilization, and 2.8x lossless digital zoom. Flight plans and parameters for survey reaches were pre-planned using Pix4Dcapture. Defined transects, set waypoints, altitudes, and speed over the ground were monitored to ensure the aircraft flew survey locations in the same manner during each survey. Flight plans had a minimum of 90 percent forward overlap and 70 percent side overlap to ensure enough overlap of the river to produce quality orthomosaics. All flights were flown with a nadir camera angle and a circular polarized lens was used for most flights. Several trial flights were made prior to the spawning season in mid-August to adjust variables and determine the minimum resolution required. Ultimately, a specified ground level of 30.5 meters (100 feet) was decided to provide quality images while also ensuring enough clearance of surrounding trees. The number of images taken for each survey reach varied depending on the area and flight plans (upstream reach ~ 55 images; middle reach ~ 85 images; downstream reach ~ 234 images). Five ground control points were placed throughout the surveyed reaches (upstream reach – 1 marker; middle reach – 2 markers; downstream reach – 2 markers) prior to UAV surveys and georeferenced using an Arrow RTK GNSS Receiver. All image files were saved onto a computer hard drive for safe storage. The flight crew consisted of two individuals, a remote pilot and a visual observer. The pilot was a certified remote pilot under the Federal Aviation Administration's (FAA) Code of Federal Regulations Title 14, Part 107 rule for UAV/UAS pilots.

Digital orthomosaics were created for each spawning reach surveyed with the UAV using Agisoft Metashape Professional v1.8.1 photogrammetry software. Images were aligned with high accuracy using generic preselection with a key point limit of 40,000 and a tie point limit of 4,000. Markers were autodetected and corrected as needed to reduce pixel error. Camera calibrations were conducted to optimize the final camera model. A high-quality dense point cloud, digital elevation model (DEM), and orthomosaic were created for each weekly survey. All orthomosaics were exported as GeoTIFF files and opened in ArcGIS Pro v3.2 for subsequent analyses. The georeference tool in ArcGIS Pro was used to georectify imagery week-to-week using locations associated with distinct features present in weekly surveys. Four separate observers reviewed the orthomosaics independently in ArcGIS Pro. Redds were digitized by each observer for each weekly survey. Orthomosaics of the same survey locations from sequential flights were sometimes overlayed or viewed simultaneously, side by side, if needed, to determine weekly changes in the spatial pattern of redd locations. This aided in the identification of newly constructed redds that overlapped with previously constructed tule redds during the monitoring period (i.e., week of October 9 through week of November 22). Observers were able to review the georeferenced images multiple times, zooming in and panning as needed, to allow redds to be quantified more clearly.

Aerial Survey Identification of Redds

Observers identifying redds from orthomosaics made redd counts independently from each other and ground surveyors. The four observers had varying levels of experience identifying redds: from no experience at all to years of experience counting redds using both field methods and counts from aerial imagery. Initial instructions were provided on accessing ArcGIS Pro project files for each observer and how to identify fall Chinook salmon redds from aerial imagery based on their appearance lighter in color than the surrounding substrate and possible presence of a fish sitting on or slightly behind the redd. Other tips were provided such as panning in and out to view all the available spawning habitat and setting the project background to be dark or turning off the lights in the room to allow better image contrast. Observers were asked to draw a polygon around each redd using the Create Features tool in ArcGIS Pro. Redds observed during surveys from September 5 through October 3 were designated as tule redds and redds first identified from October 13 through November 20 were designated as URB redds. After identifying all redds for a particular survey, aerial observers indicated the survey date when the redds were observed in the attribute tables associated with each feature layer. Observers reviewed all the imagery in sequential order for one survey reach (e.g., upstream reach) before progressing to the other survey reaches. This was done to help observers remember redd locations and assess changes (i.e., new redds) made week to week. If fish were present on a redd or areas looked recently cleared two weeks (i.e., two survey dates) after the redd was initially observed, then observers were asked to create a new polygon designating a new redd. In general, this corresponded with fish residence times and the age of redds observed in the field before they began to no longer be discernable, though times varied depending on stream flow and periphyton accumulation.

Aerial Survey Documentation of Superimposition

An independent person, not one of the four aerial observers, assessed the overlap of redds initially identified during surveys from September 5 through October 3 (i.e., tule redds) with redds later identified during surveys from October 13 through November 20 (i.e., URB redds) to document superimposition. The area (m^2) of each tule redd was first calculated in ArcGIS Pro. If a tule redd was later overlapped by a URB redd, then the Measure Area tool in ArcGIS Pro was used to measure the area of overlap. Tule redds with greater than 50 percent overlap among redds were identified as superimposed.

Comparative Analysis

Total tule redd counts were compared among aerial and ground surveys along with counts of redd superimposition. Initially, redd counts from the total area of the three designated survey reaches were compared among methods. However, some areas within each reach were inaccessible during ground surveys due to higher flows or deep water. Therefore, redd counts were also compared from only areas that were accessible during ground surveys to ensure areas being compared were the same among survey methods. Variability in observer redd calls measured by the coefficient of variation (CV) were also calculated for each survey reach and combined across all survey reaches for comparisons among observers and reaches.

RESULTS

Environmental Conditions

Mean daily White Salmon River discharge measured at RM 1.9 averaged 608 cfs in September, 601 cfs in October, and 800 cfs in November. River discharge during the low flow months of September and October ranged from 570 cfs to 695 cfs (Figure 3). On November 2, river discharge increased to 802 cfs due to heavy rains and continued to climb until peaking on November 7 at 1,203 cfs. The river discharge slowly declined over the following three weeks to 690 cfs on November 21 and 639 cfs on November 27. Surveys conducted during high water events had reduced water clarity making identification of redds from both aerial and ground surveys difficult.

Mean daily river temperatures averaged 8.1°C from September 8 through November 21. Temperatures steadily declined over the study period from a starting temperature of 10.1°C to a final temperature of 5.5°C (Figure 4). Temperature data was used to estimate days until fertilized tule eggs hatched. A previous study developed an index relating developmental stages of hatchery reared fall Chinook salmon embryos to time and temperature (e.g., degree days) (Boyd et al. 2010). A degree day in this case was defined as the mean daily temperature above 0°C. Based on the relationships observed, time until 50 percent hatch of the fall Chinook salmon embryos was 533 degree days (Boyd et al. 2010). Water temperatures in the experimental study were similar to those observed in the White Salmon River, varying from 3.9°C – 11.7°C (mean = 8°C) (Boyd et al. 2010). Based on this information, eggs buried in tule redds on the White Salmon River would still have been present through the end of the monitoring period (Figure 4). Fertilized embryos from tule redds first observed on September 20 would not have hatched (i.e., reached 533 degree days) until approximately November 27.

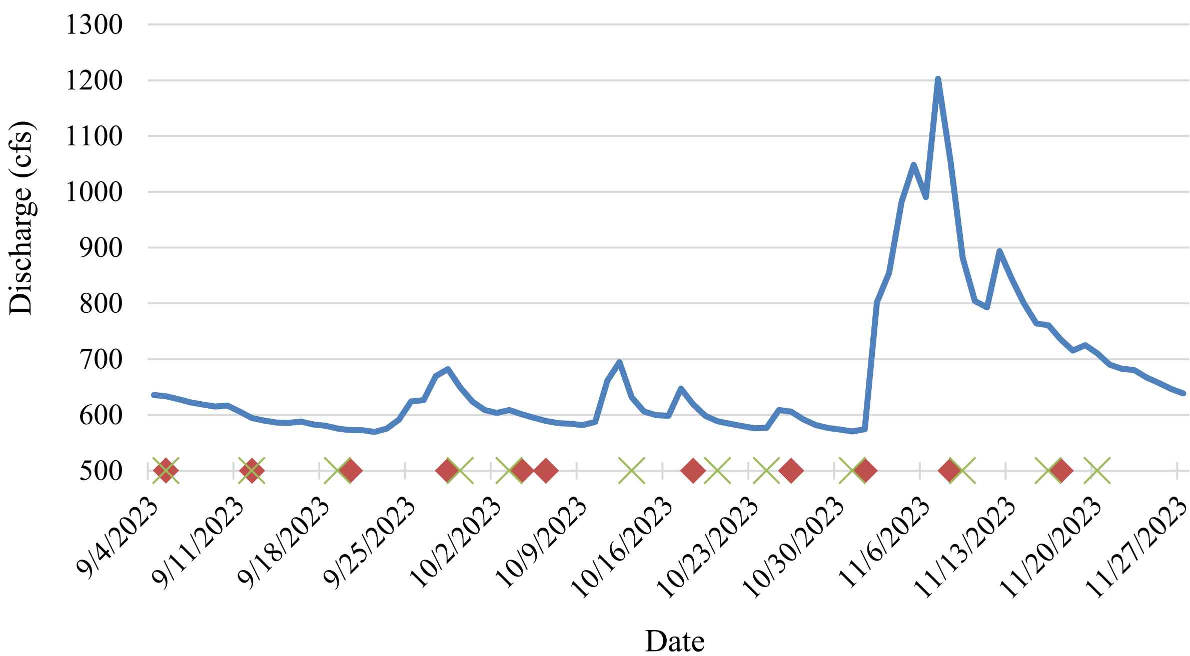

Figure 3. White Salmon River mean daily discharge (cfs) at RM 1.9 from September – November 2023. Red diamonds indicate ground survey dates and green X's indicate aerial survey dates.

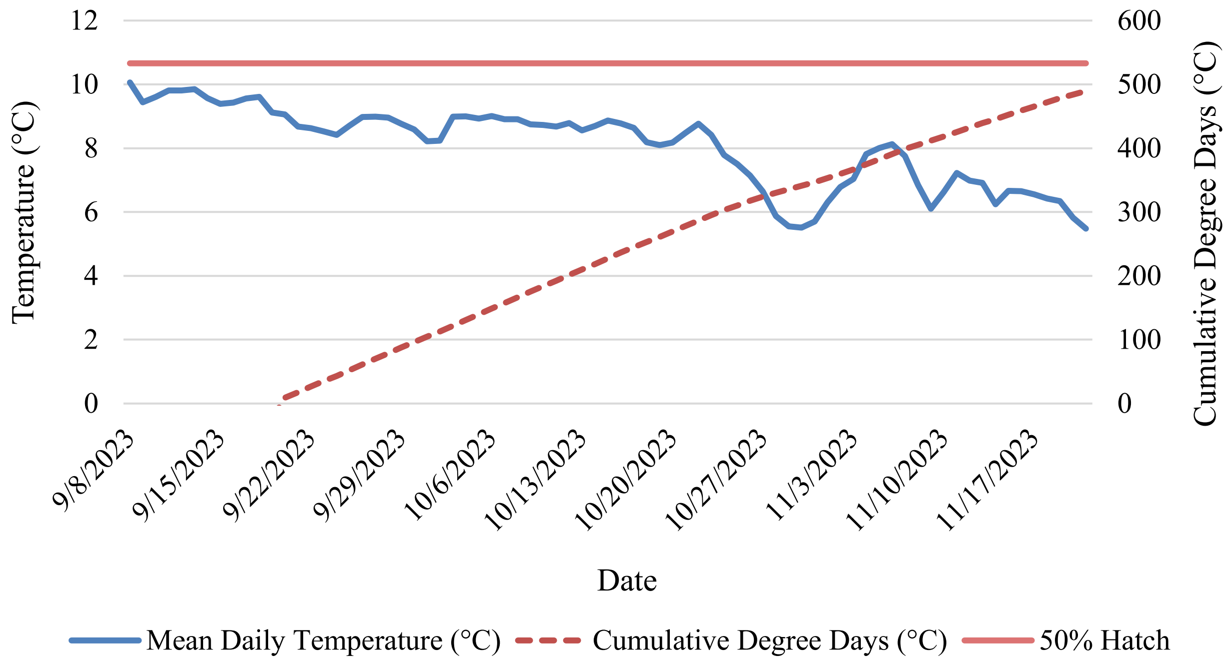

Figure 4. White Salmon River mean daily temperature (°C) and cumulative degree days for embryos in tule redds first observed on September 20. The solid pink line designates the number of degree days for 50 percent of embryos to hatch.

Ground Survey Redd Counts

No mature redds were found during the first two ground surveys on September 5 and September 12. The first complete tule redds were observed on September 20 (n = 13 redds). Over the following two weeks the number of new tule redds increased by 12 redds on September 28 and 22 redds on October 4. A total of 47 tule redds were recorded across all three reaches from the first survey event on September 5 to the cut-off date on October 6 (Table 2). Spawning pairs and/or spawning groups were observed on 18 of the redds surveyed. Additional tule redds were observed after October 6, but were not included in the assessment of redd superimposition. This was due to the similarity in appearance of tules and URBs that can make it difficult to determine the identity of spawners, especially when the two fall Chinook spawning runs overlap. Hybrid individuals may also comprise a component of the spawning population in middle to late October (Mussmann et al. 2023). In 2023, URBs were first seen within the surveyed reaches on October 6 and the first complete URB redds were documented during ground surveys on October 18.

Tule redds identified in September through the first week of October were subsequently monitored for superimposition in mid-October through November. No ground surveys were conducted the second week of October (i.e., week of October 9) due to personnel scheduling conflicts. Since no ground surveys were completed this week, there was an additional week separating previously identified tule redds from the superimposition monitoring period. Several surveys conducted during this period had reduced water clarity due to high water events making field documentation of disturbance to redds difficult. Final determinations of redd superimposition were largely made based on the location of egg pockets and the degree of overlap in perimeter boundaries of tule and URB redds recorded in the field. Across all surveyed reaches, a total of 44 tule redds were superimposed, meaning they had greater than 50 percent overlap observed among redds (Table 2). This represented 94 percent of the 47 tule redds observed through the first week of October and monitored over the study period.

Aerial Survey Redd Counts

The first tule redds identified by aerial observers were from the middle reach (n = 5 redds) and downstream reach (n = 2 redds) on September 12. Redd counts were quite variable among the four aerial observers (Tables 2 – 4). Total counts of tule redds across all three survey reaches ranged from 15 to 105 redds, with an average of 43 tule redds for the total survey area (Table 2). Average tule redd counts of the four observers were similar among reaches: upstream reach (average = 12 redds), middle reach (average = 16 redds), and downstream reach (average = 15 redds) (Table 2). Counts of URB redds varied among observers from 62 to 364 total URB redds, with an average of 154 total URB redds across all three survey reaches (Table 4). The average number of URB redds observed was highest for the downstream reach (average = 75 redds), followed by the middle reach (average = 48 redds), and upstream reach (average = 30 redds) (Table 4). Counts of redd superimposition among observers ranged from 4 to 86 redds, with an average of 28 tule redds superimposed across the entire survey area (Table 2). No tule redds were identified as superimposed for the upstream reach by three of the four observers (Table 2).

As mentioned, variability in redd counts from drone imagery was considerably high among the four aerial observers (Tables 2 – 4). One observer had consistently higher redd counts for each reach (e.g., observer 1), while the other three observers had consistently lower redd counts. Variation among observers was higher for counts of redd superimposition than tule or URB redd counts (Tables 2 – 4). The coefficient of variation (CV) among the four aerial observers across all survey reaches was 93 percent for URB redd counts, 98 percent for tule redd counts, and 143 percent for counts of redd superimposition (Tables 2 and 4). By survey reach, variation in tule redd counts was highest for the upstream reach (CV = 130 percent), followed by the middle reach (CV = 92 percent), and downstream reach (CV = 82 percent) (Table 2). Variation in redd superimposition counts followed a similar pattern, with variation highest for the upstream reach (CV = 200 percent), followed by the middle reach (CV = 137 percent), and downstream reach (CV = 120 percent) (Table 2). Variation among observers was slightly lower, but still high (CV = 80 percent for tule redd counts and CV = 132 percent for counts of redd superimposition) when the same area surveyed during ground surveys was assessed (Table 3).

Comparison of Aerial and Ground Survey Redd Counts

Average total tule redd counts of aerial observers were lower than ground counts for each survey reach, except the upstream reach (Table 2). For the total survey area, averaged aerial observer total redd counts were similar to ground counts (ground survey total = 47 tule redds; average aerial observer total = 43 tule redds; Table 2). The number of tule redds superimposed across all three survey reaches was lower for aerial surveys compared with ground surveys: 28 tule redds superimposed for aerial surveys versus 44 tule redds superimposed for ground surveys (Table 2). Direct comparisons could not be made among methods for the number of URB redds observed because the ground crew only documented URB redds in close proximity to tule redds.

Comparisons among aerial and ground counts were less similar when the same areas that were accessible during ground surveys were compared (i.e., areas compared were the same among survey methods) (Table 3). Averaged aerial observer counts of tule redds were 1.5 times lower across all three reaches (ground survey total = 47 tule redds; average aerial observer total = 32 tule redds; Table 3). The average count of tule redds superimposed across all three survey reaches was also lower for aerial observers compared with ground surveys: 21 tule redds superimposed for aerial surveys versus 44 tule redds superimposed for ground surveys (Table 3).

Overall, the percent of superimposed tule redds was lower for aerial surveys compared with ground surveys: 66 percent weighted average for aerial observers versus 94 percent of tule redds superimposed for ground surveys (Table 5). However, the percent of superimposed tule redds varied among aerial observers, ranging from 24 percent of all tule redds (observer 3) to 90 percent of all tule redds (observer 1) (Table 5). For aerial surveys, the weighted average percent of tule redds superimposed was highest for the downstream reach (73 percent) and middle reach (72 percent), followed by the upstream reach (38 percent) (Table 5). Whereas for ground surveys, the percent of tule redds superimposed within each reach was high for all three reaches, ranging from 88 percent (upstream reach) to 100 percent (downstream reach) (Table 5).

Table 2. Number of superimposed tule fall Chinook salmon redds observed by survey method for the total survey area*. Counts of tule redds observed in each reach through the first week of October are shown in parentheses.

	Upstream Reach	Middle Reach	Downstream Reach	Total
Ground survey	7 (8)	19 (21)	18 (18)	44 (47)
Aerial observer 1	23 (35)	35 (38)	28 (32)	86 (105)
Aerial observer 2	0 (4)	4 (7)	1 (4)	5 (15)
Aerial observer 3	0 (1)	1 (10)	3 (10)	4 (21)
Aerial observer 4	0 (8)	6 (9)	9 (13)	15 (30)
Average observers	6 (12)	12 (16)	10 (15)	28 (43)
StDev observers	12 (16)	16 (15)	12 (12)	39 (42)
CV observers	2.00 (1.30)	1.37 (0.92)	1.20 (0.82)	1.43 (0.98)

* Some areas were inaccessible during ground surveys due to high flow or deep water.

Table 3. Number of superimposed tule fall Chinook salmon redds observed by survey method for the partial area surveyed during ground surveys*. Counts of tule redds observed in each reach through the first week of October are shown in parentheses.

	Upstream Reach	Middle Reach	Downstream Reach	Total
Ground survey	7 (8)	19 (21)	18 (18)	44 (47)
Aerial observer 1	9 (12)	33 (36)	20 (21)	62 (69)
Aerial observer 2	0 (4)	4 (7)	1 (4)	5 (15)
Aerial observer 3	0 (1)	1 (8)	3 (8)	4 (17)
Aerial observer 4	0 (7)	4 (7)	9 (12)	13 (26)
Average observers	2 (6)	11 (15)	8 (11)	21 (32)
StDev observers	5 (5)	15 (14)	9 (7)	28 (25)
CV observers	2.00 (0.78)	1.43 (0.99)	1.04 (0.65)	1.32 (0.80)

* Only areas that were accessible during ground surveys were included for aerial counts.

Table 4. Number of upriver bright (URB) fall Chinook salmon redds observed by aerial observers for each survey reach.

	Upstream Reach	Middle Reach	Downstream Reach	Total
Aerial observer 1	74	103	187	364
Aerial observer 2	12	25	25	62
Aerial observer 3	10	29	26	65
Aerial observer 4	25	36	63	124
Average	30	48	75	154
StDev	30	37	77	143
CV	0.99	0.76	1.02	0.93

Table 5. Percent of tule fall Chinook salmon redds superimposed by upriver bright (URB) fall Chinook in each survey reach*.

	Upstream Reach	Middle Reach	Downstream Reach	Total Survey Area
Ground surveys	88	90	100	94
Aerial observer 1	75	92	95	90
Aerial observer 2	0	57	25	33
Aerial observer 3	0	13	38	24
Aerial observer 4	0	57	75	50
Weighted average	38	72	73	66
StDev observers	38	33	32	30
CV observers	100	46	44	46

* Only areas that were accessible during ground surveys were included for aerial observer counts.

DISCUSSION

One of the main goals of this study was to assess different methodologies (ground surveys and aerial UAV surveys) for identifying superimposition of tule redds by URB fall Chinook salmon within the lower White Salmon River. The percent of tule redds superimposed across all surveyed reaches was high among both ground surveys (94 percent) and aerial surveys (66 percent) when the same areas were compared. Below we evaluate the advantages and disadvantages of each method and provide recommendations for future studies.

Aerial surveys had several advantages over ground surveys for identifying superimposition, but also had separate drawbacks and challenges. One of the key advantages of aerial surveys was the ability to expand the area surveyed to encompass larger sections of river inaccessible to ground surveys. To accurately assess superimposition, the ground crew waded survey reaches and mapped the location and perimeter around redds. Deep water and swift currents in some sections of river prevented ground surveys from accessing all spawning areas within the surveyed reaches. As a result, we would have expected tule redd counts from aerial observers to be higher due to their ability to view more spawning areas. However, tule redd counts were similar among methods for the total survey area and 1.5 times lower when the same areas were compared. Additionally, the average estimated percent of tule redds superimposed using aerial surveys across all three reaches was lower than ground surveys. Aerial observers had the opportunity to review images multiple times, zooming in and panning as needed to compare weekly surveys, potentially allowing redd superimposition to be quantified more clearly. However, the physical presence of the ground crew during weekly surveys was likely an advantage in seeing new fish occupying previously identified redds and accessing disturbance. Aerial surveys were less invasive than the ground crew which could, at times, temporarily scare fish away from guarding redds. Images archived from aerial surveys could also be used in the future for other purposes (e.g., tracking changes in available spawning habitat, alternative methods for redd identification, etc.).

Additional drawbacks associated with aerial surveys were the additional storage space and time required to process images using photogrammetry software. Georectifying imagery using photogrammetry software (i.e., Agisoft Metashape Professional) was challenging given our study design and setup of ground control markers. We were unable to geographically align redds in orthomosaics with those identified during ground surveys due to the limited number of ground control points (n = 5) spread across all three surveyed reaches. Orthomosaics created independently for each survey reach only had one or two ground control points available to georectify imagery. As a result, total redd counts were compared among aerial and ground surveys instead of direct comparisons of individual redds. Thus, we could not directly quantify aerial observer error from ground survey counts or identify the number of "true" redds missed (i.e., omissions) and false identifications. In addition to georectification, aerial surveys also had issues with lighting (i.e., glare), water clarity, and river surface rippling from wind that impacted the quality of images and final orthomosaics. Shadowing from the surrounding canyon was also a concern later in the season when days were shorter. Image blurriness caused by drone movement and/or slow camera shutter speed and image compression were other factors that impacted the resolution of images and quality of final orthomosaics.

The high variability in redd counts and counts of superimposition observed among four aerial observers (CV = 98 percent for tule redd counts; CV = 143 percent for superimposition counts) created uncertainty in the "true" number of redds present and poses a significant challenge in assessing superimposition. Lower image quality from environmental conditions (solar glare, wave action, shading, water clarity, etc.) could have impacted observer counts for some survey dates. However, other studies with relatively high aerial observer variability (CV = 37 – 50 percent) have suggested that variability was caused more by differences in interpretation of redd feature characteristics than imaging related factors (Auerbach and Fremier 2022). The consistently low or high redd counts made by some aerial observers in our study suggests that interpretation of redd features may also be a leading factor for the high variability observed. Each observer was provided initial instructions on identifying redds; however, additional in-depth training and experience identifying redds prior to analyzing aerial images could help reduce inter-observer variability and potential biases. For ground survey studies, surveyor experience has been found to be positively related to observer efficiency (Muhlfeld et al. 2006; Howell and Sankovich 2012; Murdoch et al. 2019).

While redds identified during traditional ground surveys often serve as estimates for the ‘‘true’’ number of redds, there may also be inherent uncertainty and bias with ground survey redd counts (Dunham et al. 2001; Muhlfeld et al. 2006; Howell and Sankovich 2012; Murdoch et al. 2019). In our study, we were not able to estimate uncertainty in ground surveys due to only one ground survey (i.e., one ground observer team per week) being conducted. However, the variability among aerial observer redd counts in our study (CV = 80 – 98 percent) was much higher than reported values in the literature for ground survey counts (CV = 25 percent [experienced surveyors] – 49 percent [inexperience surveyors]; Howell and Sankovich 2012). Both survey methods make assumptions about the accuracy of redd counts including the differentiation of incomplete test redds from complete redds (e.g., based on morphology and small size of test redds and/or lack of guarding female), distinguishing among redds from other species (e.g., tule versus coho salmon), and discriminating redds from instances of scour from natural hydrologic flows and features. Ground surveys have the advantage of being physically present and closer when making these assessments. However, heavy rain events and high water can reduce water clarity and visibility making identification of redds difficult for either survey method.

Regardless of the method employed, the high rates of superimposition observed raises concern over the potential impacts of URBs on the resident tule population. Water temperatures monitored during the survey period indicated that tule eggs buried in redds would not have hatched until the end of November or later and thus were vulnerable to damage. Determining the direct impacts of superimposition and measuring egg mortality were not part of the scope of this study. However, in other studies, redd superimposition has been shown to result in significant mortality by damaging and dislodging eggs (Hayes 1987; Fukushima et al. 1998; Essington et al. 2000; Hendry et al. 2004; Baldock et al. 2023). The high percentage of superimposed redds observed in this study may indicate an overall reduction in the reproductive potential of the tule population.

Recommendations

Several improvements could be implemented for the 2024 field season to evaluate survey methods more effectively. Considerations in aerial study design for flight path, above ground level (AGL) height, and camera settings could improve image quality and final orthomosaic products. For example, multiple flights could be flown over each survey reach to provide a 'cross-hatch' pattern: one flight close to ground level for greater detail/resolution (~10 – 30 ft AGL) and a second higher flight (1.5 – 2.0x initial AGL; ~20 – 60 ft AGL) to aid in the alignment process of images. A flight with the camera at a slight oblique angle (10° – 30° off vertical) could also help to reduce water glare (Joyce et al. 2019). When flying with the camera at an oblique angle the flight orientation should be directed away from the sun (i.e., in the direction of sun azimuth ± 180º). Polarized filters could also be used to reduce sun glint during image capture. Flying the drone at slower speeds with higher camera shutter speeds (≥ 1/2500) will help to reduce blurred effects. Attention should also be paid to other camera settings including focus (typically set to ∞), aperture (typically f/5 – 5/8), and ISO (typically 100 – 800). Images could also be saved as RAW files for pre-processing using Adobe Lightroom photo editing software to adjust exposure levels, remove chromatic aberrations (i.e., lens correction), and remove glare. Flight planning with a high forward image overlap (90%) and sidelap (85%) may be required to ensure that the appropriate number of tie points between images can be found, which may be particularly important when mapping submerged features and contending with sun glare (Joyce et al. 2019). Improvements made to the acquisition of images will result in higher resolution images that will greatly improve the final orthomosaics, making identification of redds by aerial observers more robust.

Additional improvements could be made during the processing and georeferencing of imagery using Agisoft Metashape Professional. A more extensive array of ground control markers could be utilized to ensure aerial imagery could be georectified with high accuracy to allow direct comparisons to ground survey data. A uniform spatial distribution of ground control points and checkpoints or validation points may be required to georeference imagery and assess error (Tonkin and Midgley 2016). The reconstruction and alignment processing of images could also be strengthened by following a four-dimensional (4D) workflow (Warrick et al. 2017; Over et al. 2021). Images from all survey events could be aligned together allowing unchanged or stable features between collections of images to be utilized. With the addition of ground control markers, aligned images from multiple surveys could be georeferenced allowing changes to be detected over time for the same surveyed reaches. This 4D approach may be advantageous over the creation of individual 3D models for each survey because gaps in the alignment due to issues with blurry images, too little overlap, varying focal length or other camera parameters could be bridged together through the augmentation of images from multiple survey photosets (Wernette et al. 2022). This allows for coverage to be maximized and a dense point cloud to be reconstructed resulting in more complete, accurate, and higher quality orthomosaics.

While some environmental conditions (e.g., glacial melt, heavy rainfall events) will reduce water clarity making identification of redds difficult in any case, improvements to the aerial study design involving acquisition of images and photogrammetric processing could greatly enhance the final orthomosaic products. This coupled with the development of a standard training program for aerial observers could ensure more accurate and precise redd counts are obtained. Additional training could be important for observers to understand how redds are formed, their characteristic features (e.g., substrate contrast, female guarding), how they change over time, and ultimately how features appear in aerial images. Observers that are familiar with the river and have previous experience conducting ground surveys could be important in improving the accuracy of aerial redd counts. While this study was focused on comparing ground surveys with aerial surveys, a combination of both approaches may be most useful for documenting redd superimposition, particularly in problematic areas like the lower White Salmon River where dense spawning and redd clustering occurs.

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