Regional Operational Plan No. ROP.SF.3F.2023.01

Paxson Lake Humpback Whitefish Abundance and Demographics, 2023

by

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and

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June 2023

Alaska Department of Fish and Game Divisions of Sport Fish and Commercial Fisheries

Symbols and Abbreviations

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	′
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	″
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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SIGNATURE PAGE

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Approval

Title	Name	Signature	Date
Project Leader	Corey Schwanke		
Biometrician	Matt Tyers		
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ABSTRACT

This study will use mark-recapture methodology (two-event Petersen experiment) to estimate the abundance and length composition of humpback whitefish *Coregonus pidschian* within Paxson Lake. The marking event will occur in late May and early June 2023 and will consist primarily of using entanglement nets to capture whitefish. The recapture event will take place from November 2023 through January 2024 and will consist of sampling subsistence-harvested fish. ADF&G staff will also capture, sacrifice, and sample an additional 225–300 fish during the recapture event to estimate sex composition, age composition, length composition, length-at-age, age-at-maturity, and length-at-maturity. Understanding humpback whitefish abundance and demographics will allow for more informed management of the subsistence fishery.

Keywords: humpback whitefish, Paxson Lake, subsistence, mark-recapture, length composition

PURPOSE

A state-managed subsistence whitefish fishery occurs from October 1 through March 31 in lakes within the Upper Copper/Upper Susitna Management Area. Whitefish have become an important food source for some Alaskans, and harvests from Paxson Lake have dramatically increased in the last 5 years, with annual harvests typically exceeding 6,000 fish. The bulk of the harvest from Paxson Lake occurs during the month of December, when whitefish are concentrated for spawning, and the vast majority of the fish harvested are humpback whitefish *Coregonus pidschian*. The purpose of this study is to estimate abundance and length composition for this population, and acquire general life history information including estimates of mean length-at-age, age-at-maturity, and length-at-maturity. These demographics will be useful to assess the general resiliency of the population to exploitation, and to document potential changes in the population's abundance, length, or age structure over time.

BACKGROUND

Paxson Lake is part of the Upper Gulkana River drainage (Figure 1). It is road-accessible from the Richardson Highway, has a surface area of 1,570 ha, and has a maximum depth of 29.2 m. The outlet of Paxson lake, located at the south end, is the start of the Gulkana River mainstem, which flows 81 river kilometers (RKM) to the Copper River (Figure 1). Paxson Lake supports populations of lake trout *Salvelinus namaycush*, Arctic grayling *Thymallus arcticus*, burbot *Lota lota*, humpback whitefish, and round whitefish *Prosopium cylindraceum*. Although humpback whitefish are rarely targeted by sport anglers, a state subsistence fishery occurs from October 1 through March 31. This subsistence fishery grew substantially in users and fish harvested in the last 5 years. While harvest information for 2022 is not yet complete, nearly 25,000 whitefish were reported harvested during the previous 4 years (2018–2021; Table 1; Somerville and Hansen 2021). Additionally, a record number of permits (58) were issued for the 2022 regulatory year. Gillnets are the primary gear type used in this fishery, and the household limit of whitefish is 1,000 fish annually.

This study follows a 2021 study in which seasonal distribution was characterized with the use of radiotelemetry; spawning locations were located, and age and sex composition information was collected from a sample of 200 fish netted from the spawning grounds in December 2021. Primary results were 1) the majority of fish spawn at a single location at the south end of the lake (Figure 2); 2) fish concentrate in this area for up to 2 months with peak spawning occurring in late December (Figure 3); and, 3) these fish are long-lived and appear to have cohorts that help sustain the population (Figure 4). The mean length of all fish sampled was 351 mm fork length (FL) (SD=28.2) and the mean age was 18.1 years (SD= 6.9; Table 2). Females comprised a larger proportion of the sample (p=0.64; SE=0.03), were slightly older on average (age=18.7; SE=0.64 years) than males (age=16.9; SE=0.74), and were slightly shorter on average (FL=347; SE=1.8) mm than males (FL=354; SE=3.2) mm (Table 2). Age-at-length, age-at-maturity, and length-at-maturity have not been estimated yet.

This study will estimate the abundance and length composition of mature-sized (≥315 mm FL) humpback whitefish in Paxson Lake using Petersen two-event mark-recapture techniques. This length was chosen because all but 3 of the 200 fish sampled from the spawning grounds in 2021 were ≥315 mm FL. An additional 225 specimens will be captured in the second event and sacrificed to estimate age composition, length-at-age, age-at-maturity, and length-at-maturity.

OBJECTIVES

The primary objectives of this study are to:

1) Estimate the abundance of mature-sized humpback whitefish such that the estimate is within 40% of the true value 90% of the time;
2) Estimate the length composition of the spawning population of humpback whitefish such that the estimated proportions are within 8 percentage points of the true values 95% of the time; and,
3) Estimate the age and sex composition of the spawning population of humpback whitefish in December 2023 such that the estimated proportions are within 8 percentage points of the true values 95% of the time.

The secondary objectives of this study are to:

1) Estimate mean length-at-age of humpback whitefish subject to sampling in December;
2) Estimate the length of humpback whitefish subject to sampling in December corresponding to a 50% probability of maturity; and,
3) Estimate the age of humpback whitefish subject to sampling in December corresponding to a 50% probability of maturity.

METHODS

STUDY AREA

Paxson Lake (Figure 1) is located approximately 5 km south of the junction between the Denali and Richardson Highways. It is approximately 16 km in length and relatively narrow with a near-constant width of <1.25 km. The entire body of water will be the study area for the mark-recapture study. For specimen collection to determine basic life history characteristics, humpback whitefish will be collected from the south end of Paxson Lake where whitefish are known to concentrate and where lake ice tends to be thinner. This is the general location where the majority of the winter subsistence harvest occurs.

EXPERIMENTAL AND SAMPLING DESIGN

This study will use mark-recapture techniques to estimate abundance of humpback whitefish in Paxson Lake. Humpback whitefish will be captured and tagged during early summer (May and June 2023) across the lake for the marking event. The lake will be divided into 4 equal-sized quadrants that will serve as initial strata for diagnostic testing (Figure 2). The second event will be slightly unorthodox, with the entire event consisting of sampling fish from the spawning area on the extreme south end of the lake. Most samples will come from the gillnet subsistence fishery during early winter 2023 (mid-November through early-January). Additionally, 225–300 fish will be captured and sampled from the same location by ADF&G staff during the same time period for both mark-recapture and secondary objectives.

Assumptions needed to garner an unbiased estimate of abundance using Chapman's modification of the Petersen estimator (Seber 1982) are listed below.

1. the population is closed (humpback whitefish do not enter the population, via growth or immigration, or leave the population, via death or emigration, during the experiment);
2. all humpback whitefish will have a similar probability of capture in the first event or in the second event, or marked and unmarked humpback whitefish will mix completely between events;
3. marking of humpback whitefish will not affect the probability of capture in the second event;
4. marked humpback whitefish will be identifiable during the second event; and,
5. all marked humpback whitefish will be reported when recovered in the second event.

Failure to satisfy these assumptions may result in biased estimates; therefore, the experiment is designed to allow the validity of these assumptions to be ensured or tested. Sufficient data will be collected to perform diagnostic tests to identify heterogeneous capture probabilities (violations of Assumption 2) and prescribed model selection procedures will be followed in the event of such violations. Diagnostic tests are not available to evaluate Assumptions 1, 3, 4 and 5; instead, the experiment is designed to ensure that these assumptions will be met thereby minimizing potential biases. The design will ensure that sample sizes will be adequate to meet objective precision criteria and to perform reliable diagnostic tests.

***Assumption 1**:* A previous telemetry study[1] suggested that the humpback whitefish population in Paxson Lake is closed. No radiotagged humpback whitefish emigrated from Paxson Lake during this 18-month long study. Because of this, it is assumed that no humpback whitefish immigrate to the lake because short-term movements should have also been captured during the telemetry study. Immigration due to growth recruitment is expected to be insignificant (e.g., ~5 mm of growth between capture events) because these fish are long-lived and relatively slow growing (Table 2). Nevertheless, the presence of growth recruitment will be tested, and if significant, the associated fish will be culled from the data set or the minimum length limit will be adjusted. Emigration due to natural mortality is also assumed to be negligible because of the longevity of these fish.

[1] Corey Schwanke, Fishery Biologist, Paxson Lake humpback whitefish demographics, seasonal distribution, and spawning locations, unpublished data, 2022.

Subsistence mortality will certainly exist and will be monitored through the in-place permit system. If subsistence mortality is high, and we conclude that immigration is insignificant and/or cull growth recruitment, the estimate will be unbiased and germane to the first event.

Assumption 2: Differences in capture probability related to fish size, location, and time will be examined. Size-selective sampling will be tested using 2 Kolmogorov-Smirnov tests. The tests and possible actions for data analysis are outlined in Appendix A1. If stratification by size or location is required, capture probability will be examined for each stratum, and total abundance and its variance estimate will be calculated by summing strata estimates. The assumption of equal probability of capture (or complete mixing) should be satisfied with this study design. This mark-recapture experiment is unconventional in that first event marks will be spread across the lake, but fish will be examined during the second event at a single location in the lake. Because of this, some tests typically used to evaluate consistency will not be performed (Appendix A2). The Complete Mixing Test (SPAS terminology, Appendix A2) will be used to test for equal probability of capture in the second event among first-event stratum because it does not require strata in the second event, and is therefore suitable for this study design. The Mixing Test and Equal Proportions Test (SPAS terminology, Appendix A2), however, will not be possible within the bounds of this study design. In the absence of these tests, a 1x4 chi-square goodness-of-fit test with the number of fish recaptured in section D (the spawning area) originally tagged in sections A–D (throughout the entire lake) will be used to provide some information on the extent of mixing. Also, a previous telemetry study[1] demonstrated that fish radiotagged throughout the lake in May and June did adequately mix at the spawning area on the south end of the lake during the spawning period.

Assumption 3: No handling and marking induced behavioral effects are anticipated. In the rare event a fish appears injured or overly stressed it will not be tagged.

Assumption 4: This assumption will be addressed by double-marking each humpback whitefish captured during the first event. Fish will receive an individually numbered Floy tag for the primary mark and an adipose clip for the secondary mark. Tag loss will be noted when a fish is recovered during the second event with a secondary mark but without a Floy tag. In addition, tag placement will be standardized, which will enable the fish handler to verify tag loss by locating recent tag wounds. Tag loss is anticipated but is expected to be minimal.

Assumption 5**:** All fish will be thoroughly examined for tags or recent fin clips. All markings (tag number, tag color, fin clip, and tag wound) for each fish will be recorded.

Fish Capture

Several gear types will be available to capture fish for the marking event, but entanglement nets (2.5–2.85 cm bar mesh) that are 125 ft long will likely be the primary gear type used. This mesh size should minimize size-selectivity (R. J. Brown, Fishery Biologist, United States Fish and Wildlife Service (USFWS), Fairbanks, personal communication). Although entanglement nets will likely have the highest catch rates, other gear types such as beach seines and electrofishing will also be used where possible (i.e., in shallow sections of the lake). Effort will be made to disperse tags throughout the lake while ensuring each quadrant of the lake has sufficient sample sizes for diagnostic testing (e.g., >200 fish for each quadrant). Based on catch rates from the previous study[1] it is believed more humpback whitefish reside on the north and south ends of the lake than the middle of the lake; therefore, it is anticipated that more tags will be deployed in sections A and D (Figure 2). Various nets with different mesh sizes will be used for the second event because we will be sampling the catch of many subsistence users. Gillnets with a bar mesh less than 5 cm are the legal gear for the subsistence fishery. It is not known what size nets subsistence users will deploy, but diagnostic tests (i.e. K-S tests) will be conducted to test for size selectivity between events.

Fish will be sampled from the south end of Paxson Lake during the second event to collect information on life history. A crew of 3–4 people will sample humpback whitefish with 2.5-cm bar mesh entanglement nets from the south end of Paxson Lake. It is important to sample all mature length classes to accurately assess length/age-at-maturity. Sampling will take place for 1–2 nights on a weekly basis for 3 weeks starting in December.

Sample Size

Very little is known about the size of the humpback whitefish population in Paxson Lake, but there are several indicators that it is relatively large. First, catch rates for humpback whitefish in entanglement nets during a previous spring-time lake trout study were very high. Although records were not kept for whitefish catches, they were considered a nuisance while trying to target lake trout. The most telling information about abundance approximation is the harvest in the subsistence fisheries. Over 30,000 fish were likely harvested in the last 5 years, and catch rates appear to still be high, suggesting that the population has not been meaningfully depleted. Additionally, a previous telemetry study[1] only had 2 radio tags captured and returned by subsistence participants during the first year of the study despite having up to 40 radio tagged fish concentrated in the spawning area for several weeks. During this time period, nearly 4,000 fish were harvested. Considering this as a very crude Petersen experiment would yield a population estimate of well over 50,000 fish. Although we cannot assume every tag from a harvested fish was returned, a fish-by-fish analysis showed that the vast majority of those radiotagged fish that went to the spawning area remained in the lake post spawn.

A conservative guess on the population size of mature-sized humpback whitefish (≥315 mm FL) is >100,000, and it could be as high as 200,000. Assuming a midpoint of 150,000 fish, a sample of 1,727 fish would need to be sampled in each event to meet the precision criteria listed in Objective 1. Assuming that samples will be more easily attained from the subsistence fishery (second event), a plausible expectation is to sample up to 1,500 fish in the first event, and examine 2,000 fish in the second event. If tagging rates are lower in the first event (e.g., 1,000 fish), then 3,000 fish will need to be examined in the second event. As with any mark-recapture experiment, effort in the second event can be adjusted to ensure precision criteria are met.

Using the methods of Thompson (1987), ages from approximately 225 otoliths (3 weekly samples of 75) paired with length and maturity information will be sufficient to estimate age, sex, and length composition of the sample with an accuracy of at least ±8 percentage points at the $\alpha = 0.05$ significance level. All samples will be collected during 3 separate weekly trips to expected spawning locations starting in early December, and 75 fish will be sacrificed each week.

DATA COLLECTION AND REDUCTION

For each humpback whitefish captured and tagged in spring 2023, data collected will include: 1) date; 2) gear type; 3) measurement of fish length to the nearest 1 mm FL; 4) location (quadrant and GPS coordinates in WGS84 decimal-decrees); and, 5) Floy tag number. In addition to Floy tagging, a secondary mark will be given to these fish in the form of an adipose fin clip. This will enable us to determine if the fish was marked during this event, even if tag loss occurs.

All fish examined in the second event will have the same information recorded, but no secondary mark will be used because all fish will have been harvested.

Humpback whitefish captured in December 2023 will be sacrificed and sampled for length, sex, maturity (yes or no), and the otoliths will be removed for aging. All fish will be visually inspected for gamete development and subcategories will be designated for all female fish deemed to be spawners. Subcategories will include ripe (estimated >90% of eggs present), partial (estimated 10–90% of eggs left), or spent (<10% of all eggs remaining). Sagittal otoliths will be removed from heads collected in the field and aged by counting annuli as described by Chilton and Beamish (1982).

All data will be entered into a Microsoft Excel workbook with columns for date of capture, gear type, location, length, sex, maturity (mature or not mature), spawning condition, and age for each whitefish sampled.

DATA ANALYSIS

Abundance

Abundance will be estimated using Chapman's modification of the Petersen two-sample model (Seber 1982). This estimate will be calculated using:

$$\hat{N} = \frac{(n_2 + 1)(n_1 + 1)}{m_2 + 1} - 1 \qquad (1)$$

where:

$\hat{N}$ = the abundance of humpback whitefish in the study area;

n_1 = the number of humpback whitefish marked and released during the first event;

n_2 = the number of humpback whitefish examined for marks during the second event; and,

m_2 = the number of humpback whitefish recaptured in the second event.

The variance of this estimator will be calculated as:

$$V\hat{a}r\left[\hat{N}\right] = \frac{(n_1 + 1)(n_2 + 1)(n_1 - m_2)(n_2 - m_2)}{(m_2 + 1)^2 (m_2 + 2)} \qquad (2)$$

In the event that Kolmogorov-Smirnov or Chi-squared tests indicate evidence of unequal capture probabilities by physical or spatial strata, a stratified or partially stratified (Darroch 1961) estimate will be used instead, as outlined in Appendix A1.

Length Composition

Kolmogorov-Smirnov test outcomes will be used to determine if stratification is necessary and if data from the first, second, or both events are to be used. For cases I–III (Appendix A1) stratification is not necessary and length proportions and variances of proportions for humpback whitefish will be estimated using samples from the event(s) without size-selectivity using:

$$\hat{p}_k = \frac{n_k}{n} \tag{3}$$

where:

$\hat{p}_k$ = the proportion of humpback whitefish that are within length category k (25 mm increments);

n_k = the number of humpback whitefish sampled that are within length category k; (25 mm increments); and,

n = the total number of humpback whitefish sampled.

The unbiased variance of this proportion is estimated as (Cochran 1977):

$$\hat{V}[\hat{p}_k] = \frac{\hat{p}_k(1-\hat{p}_k)}{n-1} \tag{4}$$

Demographics

The proportion of fish in a life-history category j (i.e., proportion of fish of a given age and the proportion of fish that are mature), will be estimated as:

$$\hat{p}_j = \frac{n_j}{n}, \tag{5}$$

where:

n_j = the number of humpback whitefish sampled at age or maturity j; and,

n = the total number of humpback whitefish sampled.

The variance of this proportion will be estimated as:

$$\hat{V}(\hat{p}_j) = \frac{\hat{p}_j(1-\hat{p}_j)}{n-1}. \tag{6}$$

The proportions of fish of each sex and the associated variances will also be estimated using equations (3) and (4), with appropriate substitutions.

The length or age corresponding to 50% maturity will be estimated using a Bayesian logistic regression model:

$$Y_i \sim Bern(\pi_i). \tag{7}$$

$$log\left(\frac{\pi_i}{1-\pi_i}\right) = \beta_0 + \beta_1 X_i. \tag{8}$$

where:

Y_i = maturity of fish i,

X_i = length or age of fish i;

π_i = probability of maturity associated with fish i; and,

β_0 and β_1 represent regression coefficients, and will be modeled with diffuse Normal priors.

JAGS model code (Plummer 2003) is included in Appendix B. The length or age corresponding to a 50% probability of maturity L_{50} can be calculated as below, and this calculation is embedded in the model code. The standard error and associated credible interval will be calculated (vector-wise) from the vector of Markov Chain Monte Carlo (MCMC) samples for L_{50}.

$$L_{50} = -\frac{\beta_0}{\beta_1}. \quad (9)$$

For each age class a, mean length-at-age will be estimated as:

$$\overline{X}_a = \frac{1}{n_a}\sum_{i=1}^{n_a} X_{ai} \quad (10)$$

where:

n_a = the number sampled humpback whitefish a years old; and,

X_{ai} = the fork-length of fish i in the associated sample.

Similarly, the sample standard deviation of the length-at-age estimates will be calculated as:

$$S_a = \sqrt{\frac{1}{n_a-1}\sum_{i=1}^{n_a}(X_{ai} - \bar{X}_a)^2} \quad (11)$$

for each age class.

SCHEDULE AND DELIVERABLES

Dates of sampling events, milestones, and other activities are summarized in the following table.

Date(s)	Sampling Activity/Milestone
1 May 2023	Complete Operational Plan
25 May–15 June 2023	Conduct marking event
November 2023–January 2024	Conduct recapture event and demographic sampling
December 2024	Data analyses complete
March 2025	FDS report complete

RESPONSIBILITIES

ADF&G

Corey Schwanke	Fishery Biologist 2	Overall supervision and implementation of project. Coordinate sampling schedules with project personnel.
April Behr	Fishery Biologist 3	Supervise project leader and review all reports.
Matt Tyers	Biometrician 3	Assist in preparation of statistical design of field investigation for operational plan and review data analysis and final report.
Mark Somerville	Fishery Biologist 3	Assist with second event examination
Matt Albert	Fishery Biologist 2	Assist with first event tagging
Tracy Hansen	Fishery Biologist 2	Assist with second event examination
Brian Collyard	F&W Tech 4	Assist with first event tagging
Mark Roti	F&W Tech 4	Assist with second event examination
Clint Wyatt	F&W Tech 2	Assist with first event tagging
Mike Willard	F&W Tech 3	Assist with first event tagging
Mike McNulty	F&W Tech 3	Assist with first event tagging

BLM

Tim Sundlov	Fisheries Biologist	Assist with first event tagging

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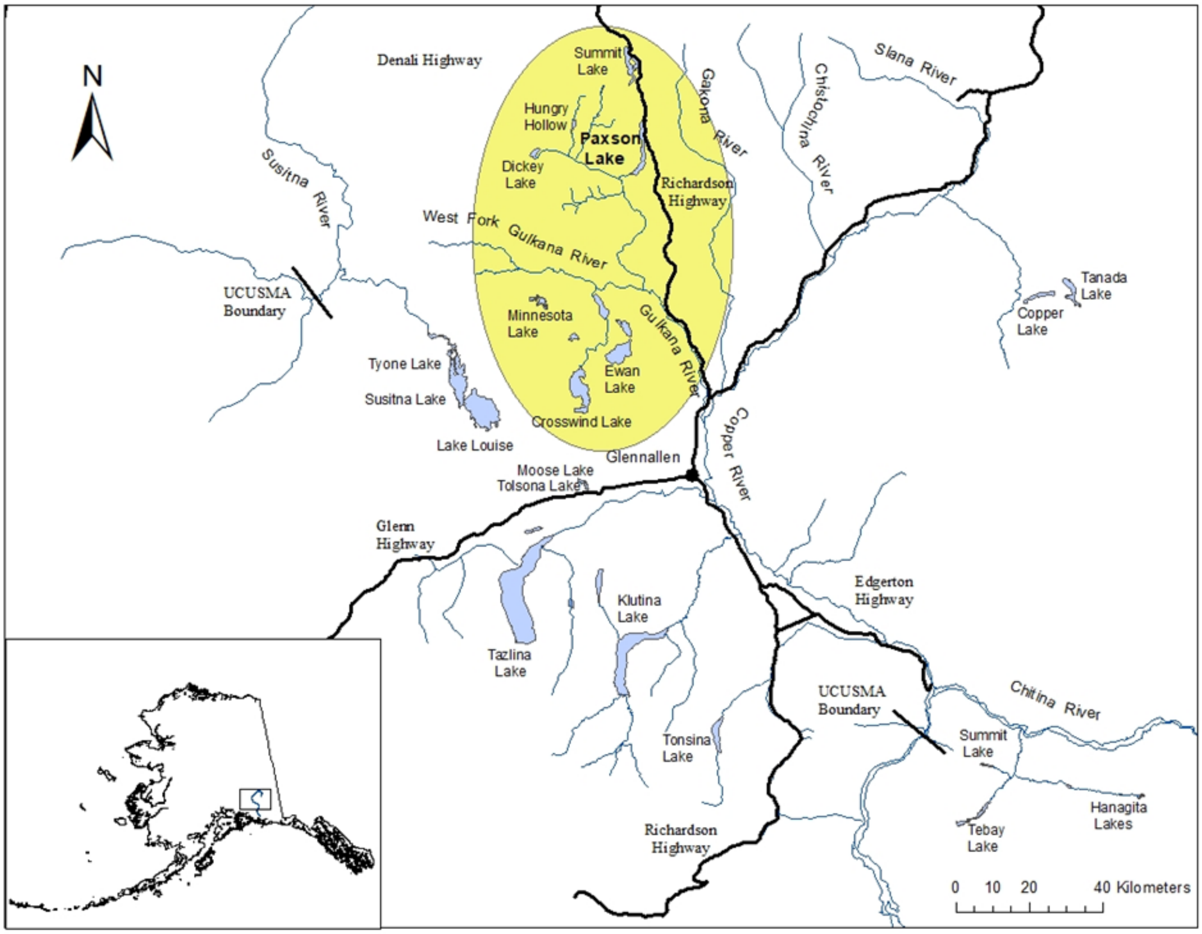

Figure 1.–Map of the Copper River drainage with the Gulkana River drainage highlighted in yellow and Paxson Lake depicted in bold.

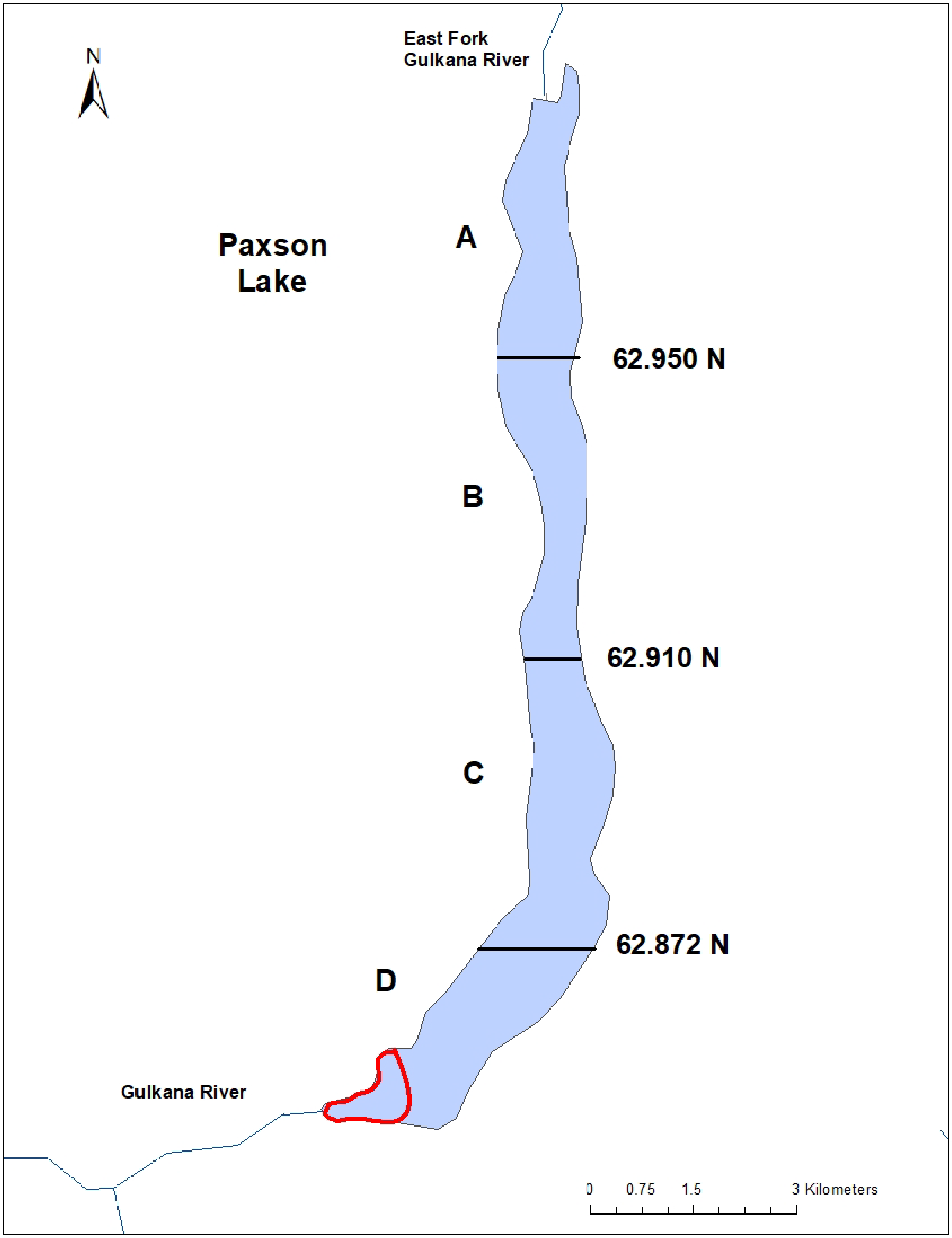

Figure 2.–Map of Paxson Lake with geographic strata (A–D) for the marking event and the recapture event (outlined in red on south end of lake).

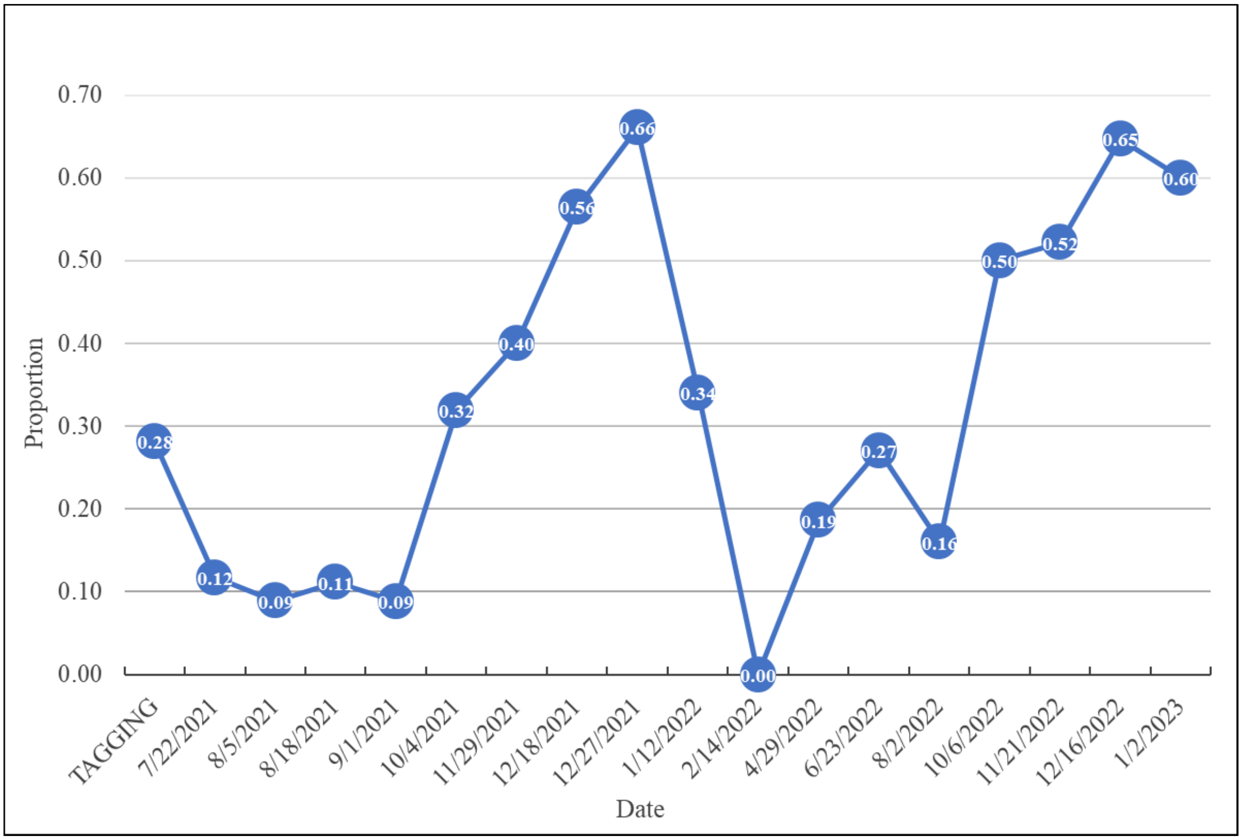

Figure 3.–The proportion of radiotagged fish found in the spawning area (outlined in Figure 2) for each tracking survey.

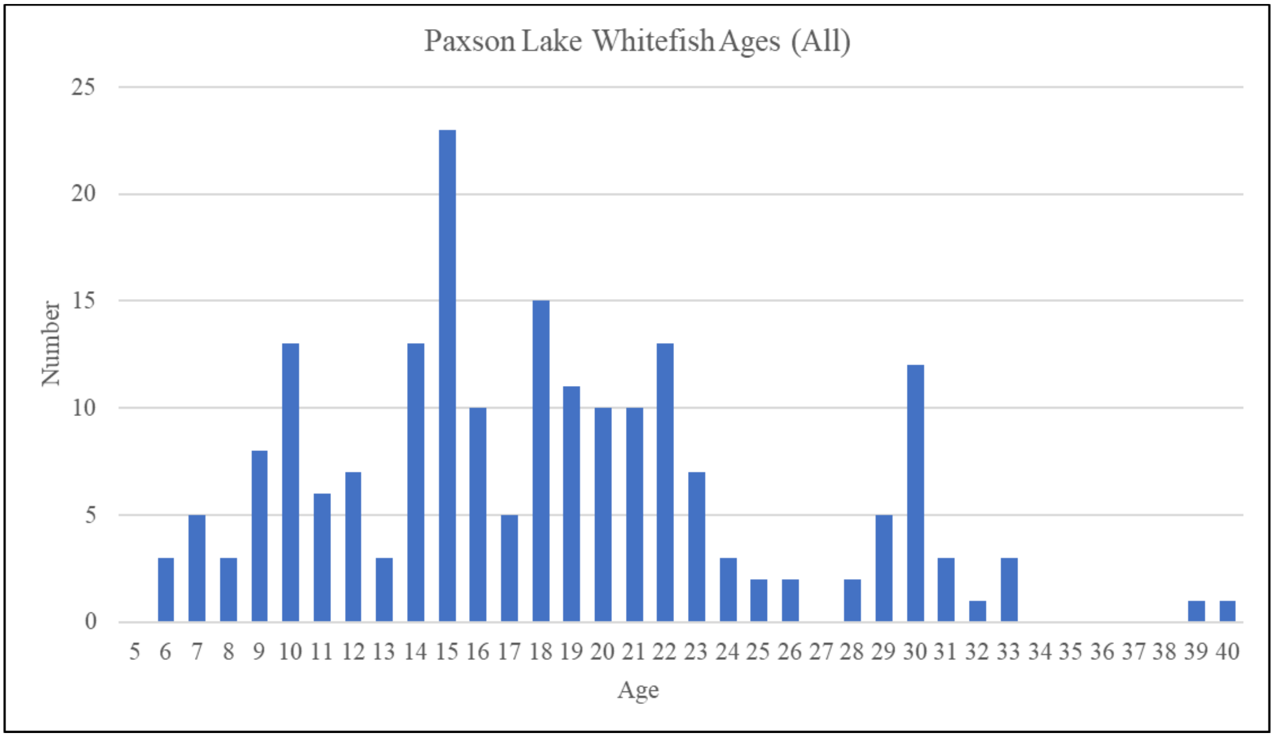

Figure 4.–Ages of 200 humpback whitefish collected from Paxson Lake on 20 and 28 December 2021.

Table 1.–Reported harvest of whitefish from the state subsistence fishery at Paxson Lake, 2010–2022.

Year	Number of successful permits	Number of whitefish harvested
2010	5	955
2011	4	333
2012	6	415
2013	6	1,060
2014	8	605
2015	5	456
2016	6	724
2017	6	983
2018	23	6,734
2019	31	6,224
2020	36	7,567
2021	26	3,906
2022	19[a]	3,115

[a] Partial numbers listed because the fishery was still open when this table was generated.

Table 2.–Mean length (mm FL) and age of whitefish captured during December 2021.

Metric	Statistic	Females	Males	All
Age	Mean	18.7	16.9	18.1
	SD	7.2	6.3	6.9
	Sample Size	128	72	200
Length	Mean	348.6	354	350.6
	SD	19.8	26.9	22.7
	Sample Size	128	72	200

APPENDIX A

Appendix A1.–Detection and mitigation of selective sampling during a two-event mark recapture experiment.

Size-selective sampling may cause bias in two-event mark-recapture estimates of abundance and size and sex composition. Kolmogorov-Smirnov (KS) two sample tests are used to detect size-selective sampling.

Results of the tests will dictate whether the data needs to be stratified to obtain an unbiased estimate of abundance. The nature of the detected selectivity will also determine whether the first, second, or both event samples are used for estimating size compositions.

DEFINITIONS

M = Lengths of fish marked in the first event
C = Lengths of fish inspected for marks in the second event
R = Lengths of fish marked in the first event and recaptured in the second event

SIZE-SELECTIVE SAMPLING: KS TESTS

Three KS tests are used to test for size-selective sampling.

KS Test 1	C vs R	Used to detect size selectivity during the 1st sampling event. H_o: Length distributions of populations associated with C and R are equal
KS Test 2	M vs R	Used to detect size selectivity during the 2nd sampling event. H_o: Length distributions of populations associated with M and R are equal
KS Test 3	M vs C	Used to corroborate the results of the first two tests. H_o: Length distributions of populations associated with M and C are equal

Table A1-1 presents possible results of selectivity testing, their interpretation, and prescribed action.

-continued-

Table A1–1 Possible results of selectivity testing, interpretation, and action.

	KS or χ^2 Test			
Case	M vs. R (2^{nd} event test)	C vs. R (1^{st} event test)	M vs. C (1^{st} vs 2^{nd} event)	Interpretation and Action
I	Fail to reject H_o	Fail to reject H_o	Fail to reject H_o	**Interpretation**: No selectivity during either sampling event. **Action**: Abundance: Use a Petersen-type model without stratification. Composition: Use all data from both sampling events.
II	Reject H_o	Fail to reject H_o	Reject H_o	**Interpretation:** No selectivity during the 1^{st} event but there is selectivity during the 2^{nd} event. **Action**: Abundance: Use a Petersen-type model without stratification. Composition: Use data from the 1^{st} sampling event without stratification. 2^{nd} event data only used if stratification of the abundance estimate is performed, with weighting according to Equations 1–3 below.
III	Fail to reject H_o	Reject H_o	Reject H_o	**Interpretation:** No selectivity during the 2^{nd} event but there is selectivity during the 1^{st} event. **Action**: Abundance: Use a Petersen-type model without stratification. Composition: Use data from the 2^{nd} sampling event without stratification. 1^{st} event data may be incorporated into composition estimation only after stratification of the abundance estimate and appropriate weighting according to Equations 1–3 below.
IV	Reject H_o	Reject H_o	Either result	**Interpretation:** Selectivity during both 1^{st} and 2^{nd} events. **Action:** Abundance: Use a stratified Petersen-type model, with estimates calculated separately for each stratum. Sum stratum estimates for overall abundance. Composition: Combine stratum estimates according to Equations 1–3 below.
V	Fail to reject H_o	Fail to reject H_o	Reject H_o	**Interpretation:** The results of the 3 tests are inconsistent. **Action:** Need to determine which of Cases I–IV best fits the data. Inconsistency can arise from high power of the M vs. C test or low power of the tests involving R. Examine sample sizes (generally M or C from <100 fish and R from <30 are considered small), magnitude of the test statistics (D_{max}), and the *P*-values of the three tests to determine which Cases I–IV best fits the data.

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COMPOSITION ESTIMATION FOR STRATIFIED ESTIMATES

An estimate of the proportion of the population in the k^{th} size category for stratified data with I strata is calculated as follows:

$$\hat{p}_k = \sum_{i=1}^{I} \frac{\hat{N}_i}{\hat{N}} \hat{p}_{ik}, \tag{1}$$

with variance estimated as:

$$var[\hat{p}_k] \approx \frac{1}{\hat{N}^2} \sum_{i=1}^{I} \left(\hat{N}_i^2 \, var[\hat{p}_{ik}] + \left(\hat{p}_{ik} - \hat{p}_k \right)^2 var[\hat{N}_i] \right) \tag{2}$$

where:

$\hat{p}_{ik}$ = estimated proportion of fish belonging to category k in stratum i;

$\hat{N}_i$ = estimated abundance in stratum i; and,

$\hat{N}$ = estimated total abundance $= \sum_{i=1}^{I} \hat{N}_i$

TESTS OF CONSISTENCY FOR PETERSEN ESTIMATOR

Three contingency table analyses are used to determine if the Petersen estimate can be used (Seber 1982). If any of the null hypotheses are not rejected, then a Petersen estimator may be used. If all three of the null hypotheses are rejected, a temporally or spatially-stratified estimator (Darroch 1961) should be used to estimate abundance.

Seber (1982) describes 4 conditions that lead to an unbiased Petersen estimate, some of which can be tested directly:

1. Marked fish mix completely with unmarked fish between events.
2. Equal probability of capture in event 1 and equal movement patterns of marked and unmarked fish.
3. Equal probability of capture in event 2
4. The expected number of marked fish in recapture strata is proportional to the number of unmarked fish.

In the following tables, the terminology of Seber (1982) is followed, where *a* represents fish marked in the first event, *n* fish captured in second event and *m* marked fish recaptured; $m_{\bullet j}$ and $m_{i\bullet}$ represent summation over the i^{th} and j^{th} indices, respectively.

I. Mixing Test

Tests the hypothesis (condition 1) that movement probabilities (θ_{ij}), describing the probability that a fish moves from marking stratum *i* to recapture stratum *j*, are independent of marking stratum: H_0: $\theta_{ij} = \theta_j$ for all *i* and *j*.

Area/Time Marking Strata *(i)*	Area/Time Recapture Strata *(j)*				Not Recaptured
	1	2	…	t	$a_i - m_{i\bullet}$
1	m_{11}	m_{12}	...	m_{1t}	$a_1 - m_{1\bullet}$
2	m_{21}	m_{22}	...	m_{2t}	$a_2 - m_{2\bullet}$
...	...	...	...	...	…
s	m_{s1}	m_{s2}	...	m_{st}	$a_s - m_{s\bullet}$

II. Equal Proportions Test[a] (SPAS[b] terminology)

Tests the hypothesis (condition 4) that the marked to unmarked ratio among recapture strata is constant: H_0: $\Sigma_i a_i \theta_{ij} / U_j = k$, where k = a constant, U_j = unmarked fish in stratum *j* at the time of 2[nd] event sampling, and a_i = number of marked fish released in stratum *i*. Failure to reject H_0 means the Petersen estimator should be used only if the degree of closure among tagging strata is constant, i.e. $\Sigma_j \theta_{ij} = \lambda$ (Schwarz and Taylor 1998; p 289). A special case of closure is when all recapture strata are sampled, such as in a fish wheel to fish wheel experiment, where $\Sigma_j \theta_{ij} = 1.0$; otherwise biological and experimental design information should be used to assess the degree of closure.

	Area/Time Recapture Strata *(j)*			
	1	2	…	t
Recaptured ($m_{.j}$)	$m_{\bullet 1}$	$m_{\bullet 2}$	…	$m_{\bullet t}$
Unmarked (n_j - $m_{.j}$)	n_1 - $m_{\bullet 1}$	n_2 - $m_{\bullet 2}$	…	n_t - $m_{\bullet t}$

III. Complete Mixing Test[a] (SPAS[b] terminology)

Tests the hypothesis that the probability of re-sighting a released animal is independent of its stratum of origin: H_0: $\Sigma_j \theta_{ij} p_j = d$, where p_j is the probability of capturing a fish in recapture stratum *j* during the second event, and *d* is a constant.

	Area/Time Marking Strata *(i)*			
	1	2	…	s
Recaptured (m_i)	$m_{1\bullet}$	$m_{2\bullet}$	…	$m_{s\bullet}$
Not Recaptured (a_i - $m_{i\bullet}$)	a_1 - $m_{1\bullet}$	a_2 - $m_{2\bullet}$	…	a_s - $m_{s\bullet}$

[a] There is no 1:1 correspondence between Tests II and III and conditions 2–3 above. It is pointed out that equal probability of capture in event 1 will lead to (expected) non-significant Test II results, as will mixing, and that equal probability of capture in event 2 along with equal closure ($\Sigma j\theta ij = \lambda$) will also lead to (expected) non-significant Test III results.

[b] Stratified Population Analysis System (Arnason et al. 1996).

APPENDIX B

Appendix B1.–JAGS code for logistic regression model.

```
model {
  for(i in 1:n) {
    y[i] ~ dbern(pi[i])
    logit(pi[i]) <- b0 + b1*x[i]
  }

  b0 ~ dnorm(0, 0.0001)
  b1 ~ dnorm(0.01, 0.0001)   # centered at 0.01 to avoid division by zero in initial step

  l50 <- -b0/b1
}
```