Prospects for Recovery and Restoration of Coho Salmon in California



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Status of coho salmon in California, USA

- Population declines, local extinctions
- Management units: Evolutionarily Significant Units (ESUs)
 - Southern Oregon/Northern California
 Coast Coho Salmon ESU (SONCC) –
 Threatened
 - Central California Coast Coho Salmon
 ESU (CCC) *Endangered*
- All populations have protected status
- Life history
 - Anadromous, reproduce in natal streams, semelparous
 - 3-year life cycle; 3 brood years, little temporal gene flow



Background: phylogeography of coho salmon in California

- 30 sites surveyed for young-of-year in 2003
- Significant hierarchical genetic structure
 - Greatest divergence at broadest geographic scale
- Klamath River basin distinct from other northern populations

Central California ESU ______ Northern California ESU ______ Klamath River basin _____



Gilbert-Horvath et al. (in press), 18 microsatellite loci

Background: phylogeography of coho salmon in California



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Background: phylogeography of coho salmon in California



Factorial Correspondence Analysis-Individual Genotypes

Isolation by distance-Coho Salmon



Strong relationship between genetic and geographic distance due to MIGRATION

Temporal Monitoring of Coho Salmon

- Survey populations at two time points
 - Time series data at a regional scale
 - Examine allele frequency change over time
- Timepoint 1: baseline sampling in rivers throughout California in 2003 (n=1,976)
- Timepoint 2: revisited same sites in 2015 (n=2,223)
 - Expanded to include Oregon sites
- Four generations between surveys
 - Sampled two cohorts of the same brood cycle

Sampling locations

- Sampled juveniles in natal streams
- Spatially stratified electrofishing protocol
- 46 sites yielded coho salmon in 2015
- n=75 maximum per site





Analytical objectives

- Analysis of family structure
- Examine patterns of population structure at multiple spatial scales
- Assess temporal stability of genetic composition of populations
- Estimate effective population size (N_e)

Genotype data: 95 SNP loci n=4,199 individuals



Results

- Sibship reconstruction: full siblings detected in almost all populations
- Mean sibship size by site ->
- Mean sibship size by year
 - 2003 = 2.2
 - 2015 = 3.3
- Family structure may obscure or distort population structure
 - Omit full sibs from population analyses (revised n=2,460)





Temporal trends in reproduction



- 32 paired temporal population samples
- Estimated number of spawning adults that produced each sample of juveniles
- Net decrease in number of spawners between 2003 and 2015

Effective population size

- Method in development: estimating N_e using the temporal method, accounting for family structure using Colony output
- Upper bound of N_e difficult to estimate due to small sample sizes



Temporal trends in reproduction, by population: estimated number of spawning adults in 2003 and 2015



Population samples (north to south)

Relative divergence between populations: distributions of pairwise *F*_{ST} estimates



F_{ST}

Mendocino Coast-CA Coho Salmon

Stronghold

Population	Coho Salmon Escapement 2009 to 2015						
	2009	2010	2011	2012	2013	2014	2015
Mendocino Coast	887	898	1427	2848	3365	869	8577
Lost Coast Diversity Strata	672	1059	1212	2756	4646	869	7991
Navarro Point Diversity Strata	158	513	542	250	578	2	586
Albion River	8	0	162	66	894	0	467
Big River	80	134	160	269	519	155	1344
Big Salmon Creek	0	NS	NS	19	0	NS	NS
Brush Creek	0	0	0	0	0	0	0
Caspar Creek ¹	6	5	27	20	10	0	40
Cottenteva Creek	0	0	NS	0	NS	0	NS
Elk Creek	NS	NS	0	NS	NS	0	NS
Garcia River	69	9	90	0	211	з	469
Greenwood Creek	9	0	NS	NS	0	NS	2
Hare Creek	NS	0	0	NS	0	0	NS
Juan Creek	NS	NS	NS	0	NS	NS	25
Little River	4	2	8	2	2	2	65
Navarro River	70	452	420	244	354	0	423
North Fork Navarro River ²	ND	ND	ND	ND	140	0	199
Noyo River	294	286	411	228	784	723	3468
South Fork Noyo River ¹	19	63	39	38	398	305	616
Pudding Creek ¹	50	9	199	415	283	0	539
Ten Mile River	0	190	395	1127	440	з	1654
Usal Creek	10	2	0	10	13	0	0
Wages Creek	0	0	0	NS	NS	0	NS

¹ Life Cycle Monitoring stream mark-recapture estimates

 2 Life O,cle Monitoring stream using area under the curve estimates since 2013 $\,$

Source: Gallagher et al. 2015

Coho Salmon Conservation Efforts

Central California Coast Coho Salmon ESU (Endangered)

Coho smolts

Warm Springs Hatchery

Big Creek Hatchery

Central California Coho Salmon Captive Broodstock Programs

- Two captive rearing programs initiated because of steep declines in mean abundance and widespread disappearance in the southern part of the ESU
- Goals are to hold individuals from small, remnant populations through high mortality life stages to ensure persistence of populations and reintroduce recently extirpated populations
- One in Sonoma County at the Warm Springs Hatchery: focused on Russian River recovery
- One in Santa Cruz County at Big Creek Hatchery (Scott Ck): focused on South of Golden Gate recovery.



Females

Genetic Broodstock Management

In use with Warm Springs, Iron Gate, Scott Creek coho

Spawning partners determined with pairwise relatedness coefficient r_{XY}

All males ranked by r_{XY} to focal female

Optimal mates, at top, are least related to focal female

Avoid mating pairs related at half-sibling or greater

Each female is mated with up to 4 males, and each male with up to 4 females Males >



P 8184F4	F_8189C6	F_81300B	F_\$18858	#_B1BIDE	F_319087	F_\$10007	F_819820	#_#109E1	F 819FD6
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M_815752	M_B1BACF	M_8265D7	M_825905	M_818085	M_8265D7	M_829F71	M_ROC1E4	M_825905	M_817930
M_8296A9	M_81872D	M_825905	M_829F71	M_82115D	M_825905	M_817939	M_608441	M_823074	M_825905
M_60DE22	M_TACEOD	M_820925	M_62AA30	M_R27EFC	M_617939	M_620925	M_82AA30	M_815752	M_827EFC
M_80F3D4	M_823790	M_815752	M_#20925	M_82494C	M_827EFC	M_825905	M_826507	M_8296A9	M_81D91E
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M_81D01E	M_824EA3	N. 8296A9	M_823074	M_8265D7	M_8296A9	M 82880C	M_82494C	M_82AA30	M_82494C
M_82494C	M_012982	M_82494C	M_82115D	M_817004	M_82115D	M_82494C	M_623074	M_823098	M 82AA30
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M 820925	M 813528	M 600622	M BOSEAG	M 815752	M 816762	M REDORE	M 81DEDA	M ADDETT	M 829771
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M_8178G7	M_912894	M_B2AR1E	M_826263	M_60F2D4	M_8178G7	M_828179	M_813868	W_828163	M_82A818
M_828C16	M_82977E	M_820163	M_825801	M_823C23	M_82508A	M_82A599	M_8250C4	M 626170	M_01C34B
M_817C04	M_819464	M_812982	M_8250BA	M_820925	M_812E28	M_82A818	M_B1BACF	M_810EDA	M_812E26
M_829C36	M_60C809	M_629EDE	M_812E28	M_813586	M_8281E3	M_82498A	M_81201D	M_80F3D4	M_817BC7
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M_016258	M_R23EEF	M_82ACF1	M_TACESE	M_82508A	M_EIDEDA	M_81G280	M 81824F	M_812E28	M_825TBR
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M_812628	M_823002	M_813528	M_01824F	M_823EEF	M_817FDC	M_3003A4	M_B11EDA	M_81D67C	M_826263
M_826C87	M_816258	M_826176	M_81067C	M_60E810	M_81D67C	M_80E810	M_829EDE	M_826C87	M_60C809
M_8130F6	M_813C16	M_013645	M_8189C6	M_BIDEDA	M_829C36	M_8199D3	M_829234	M_R249DA	M_BIBACF
M_818405	M_61DEDA	M_#1872D	M_REC348	M_6133F6	M_62AOF1	M_827080	M_823A30	M_812094	M_#1758D
M_81C348	M_8188A0	M_826265	M_826681	M_81C280	M_8249DA	M 82ACF1	M_824FEE	M_829C36	M_813586
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M 658927	M 829234	M 812854	M 60C809	M 811C32	M 81872D	M 812894	M BT7C04	M 612010	M 6133F6
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M_826881**	M_829C36	M 812910**	M 823430	M_SIMPLE"	M. KOFBOAT	M 81BACPH	M_81C818	M_813C18	M_8260C4**
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M_617623**	M_BTIEDA	W_829F7E**	M_8280A1**	M_813528**	M_8250CA**	M_8285A1**	M_60C809	M BIDACS	M SZMEP**
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M_SCOSA4**	M_829CD9	M_81300E**	M_825486**	M_825470**	W_823234**	M_822746**	M_813D6E	M_813066**	M_013174**
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M_8286A1**	M_826176	M_625498**	M_822100**	M_612910**	M_616258	M_SITFOC**	M_8280A1	M_629234**	M. RIAEAT"
M_E1DAC3**	M_823G23	AD BIBBAON	M. 811032**	M. ADGBOTH	M 81C290**	M_829F7E**	M. SODGAF	M_82508A**	M_B1D67CH
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M 624FCE**	M_60DE22**	M SIMEAT	M_81E30C**	M_REACE 1	m starten	M_8175802**	M APSOSA"	M 60E810**	M 075498**
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Variable	Estimate ± SE	p-value
Female Stream Origin [DBC]	0.022 ± 0.015	0.128
Male Stream Origin [DBC]	0.005 ± 0.011	0.612
Female Ovulation Rate	0.02 ± 0.031	0.516
Relatedness Coefficient Rxy	0.162 ± 0.057	0.004
Female Internal Hz	0.021 ± 0.07	0.760
Male Internal Hz	0.056 ± 0.059	0.345

A generalized linear model analyzing the effects of six potential predictor variables on deformity rate reveals a significant relationship between relatedness (R_{xy}) of parent pairs and alevin deformity rate in juvenile coho salmon at Warm Springs Hatchery.

Conrad JL, Gilbert-Horvath E, Garza JC (2013) Genetic and phenotypic effects on reproductive outcomes for captively-reared coho salmon. Aquaculture 404:95-104



A gallery of deformities in age 1 coho salmon





Coho Salmon are Ocean Fish





-Coho salmon (*O. kisutch*) are born in freshwater but, in California, most migrate to the sea one year after emergence and spend two years in the ocean

-Much more difficult to study them in the ocean, both because of spatial scale, but also because of lack of ability to discriminate fish from different populations

A major driver of recovery is something that we barely understand and directly influence.

Inbreeding and Marine Survival



Steelhead, Sashin Ck. Alaska; Thrower and Hard, unpublished data

Mean relatedness of Russian River broodstock





Coho Salmon Conservation Efforts

Experimental reintroduction into Salmon Creek started in 2008





Release of captively raised maturing adult coho salmon as a novel strategy for restoration and recovery

•Salmon Ck.- no coho salmon since ~1980

•Adults from Lagunitas Creek (N=152) and from the Russian River (N=158) released in December 2008

• Juveniles confirmed and sampled in two creeks, Fay Creek (N=105) and Finley Creek (N=105) in July 2009.

•Genotyped with 18 microsatellites. Data analyzed with NewHybrids. Sibship reconstruction with Almudevar & Field (1999).



Origin of coho salmon in Salmon Creek

	No.	of individuals	5			
	Russian x	Lagunitas x				
	Russian	Lagunitas	Hybrid			
Fay Ck	8	35	62			
Finley Ck	0	14	90			
-						
	No. of Matings					
	Russian x	Lagunitas x				
	Russian	Lagunitas	Hybrid			
Fay Ck	1	2	5 or 6			
Finley Ck	Ο	1	2			

NewHybrids posterior probabilities had mean of 0.99 to assigned genealogical class.



Adult Release Conclusions

- •Endangered coho salmon reproduce when released as mature adults raised entirely in freshwater
- •Coho salmon in Salmon Ck do not avoid hybridization and may prefer it
- •Hybrids have higher no. of offspring/ family
- •NewHybrids accuracy confirmed with parentage.



Coho salmon Outcrossing Experiment

Instream Survival Results



Overwinter survival rate of F1 of Russian River broodstock (RR) outcrossed with Lagunitas/Olema Creek (OL) coho



Oversummer survival rate of F1 of Russian River broodstock (RR) outcrossed with Lagunitas/Olema Creek (OL) coho



Coho salmon Outcrossing Experiment

Instream Survival Results

1.0

RRxRR
 RRxOL



Overwinter survival rate of F1 of Russian River broodstock (RR) outcrossed with Lagunitas/Olema Creek (OL) coho



Oversummer survival rate of F1 of Russian River broodstock (RR) outcrossed with Lagunitas/Olema Creek (OL) coho

Outcrossed coho salmon survive better at all juvenile life stages

Data from UC Cooperative Extension



Genetic analysis of Mattole River coho salmon young-of-year

- Baker Creek tributary, Mattole River, California
- YOY (young-of-year) were sampled
 - August 2013 (Brood year 12/13)
 - August 2014 (Brood year 13/14)
- Genetic analyses 90 SNP loci
 - Colony v2 to resolve familial relationships
 - Population assignment test using nearby reference populations
 - Ancestry analysis

Ancestry analysis (Structure v2.3.4)



Conclusions

- Regional-scale geographic structure is concordant with management unit boundary
- Statewide decrease in number of spawning adults that produced the sampled juveniles
 – Impact of 5-year drought on habitat
- Connectivity between proximate basins
- Minimal temporal structure: within-population genetic composition relatively consistent over time
- Ancestry and affiliation of small populations influenced by migrants from nearby basins

Conservation Priorities

- Habitat restoration!!!!!!
- Connectivity of populations
- Maintain remaining genetic variation
- Evaluation of strategies
 - Where are recovery efforts having a positive



California Salmon: the Future

Opportunities abound



Conservation Priorities

- Habitat restoration!!!!!!
- Connectivity of populations
- Maintain remaining genetic variation
- Evaluation of strategies
 - Where are recovery efforts having a positive



Acknowledgements

- Southwest Fisheries Science Center-NOAA/UCSC
 - Molecular Ecology Team: Eric Anderson, Ellen Campbell, Anthony Clemento, Cassie Columbus, Laney Correa
 - Landscape Ecology Team: Heidi Fish, Alex McHuron, Casey Sheridan, Emily Tucker
- California Department of Fish & Wildlife
- Tons of partners statewide



Funding Sources

National Marine Fisheries Service



California Department of Fish & Wildlife

Army Corp of Engineers



Thank you!