# Genetic profile for Livingston Stone NFH winter-run Chinook salmon

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# National Fish Hatchery Broodstock Genetic Profile

**Facility:** Livingston Stone National Fish Hatchery

**Stock:** winter-run Chinook salmon (*Oncorhynchus tshawytscha*)

**Parental stock:** Mixture of wild-spawned and hatchery-spawned individuals trapped on the mainstem Sacramento River at Keswick Dam. In a few years individuals trapped at Red Bluff Diversion Dam were also used [Ref 1].

**Year founded:** 1997 [Ref 1].

**Generation time:** 2 years (5.7%) to 3 years (91.7%) or 4 years (2.6%) [Ref 2].

**Segregation / Integration history:** Integrated. A maximum of 10% hatchery-origin adults were used as broodstock through 2009. Beginning in 2010 only natural-origin winter Chinook have been used [Ref 1]. Hatchery release numbers are limited so as to prevent genetic swamping of the wild-spawning component of the population (hatchery-origin smolts made up ~9% of the out-migrant population in 2010) [Ref 3].

**Table 1 – Broodstock* samples analyzed:**

**a) Rapid Response microsatellites [Ref 5]**

| Description | Year | n | Life stage | Data source** |
|---|---|---|---|---|
| winter-run from Keswick | 1998 | 124 | adult | UCD |
| winter-run from Keswick | 1999 | 23 | adult | UCD |
| winter-run from Keswick | 2000 | 94 | adult | UCD |
| winter-run from Keswick | 2001 | 202 | adult | UCD |
| winter-run from Keswick | 2002 | 193 | adult | UCD |
| winter-run from Keswick | 2003 | 107 | adult | UCD |
| winter-run from Keswick | 2004 | 345 | adult | AFTC |
| winter-run from Keswick | 2005 | 378 | adult | AFTC |
| winter-run from Keswick | 2006 | 268 | adult | AFTC |
| winter-run from Keswick | 2007 | 154 | adult | AFTC |
| winter-run from Keswick | 2008 | 191 | adult | AFTC |
| winter-run from Keswick | 2009 | 240 | adult | AFTC |
| winter-run from Keswick | 2010 | 416 | adult | AFTC |
| winter-run from Keswick | 2011 | 370 | adult | AFTC |

* Potential broodstock collected at Keswick Trap and assigned as "winter-run" based on the Rapid Response protocol [Ref 4]. A subset of each collection was actually used for broodstock.
** UCD = University of California at Davis; AFTC = Abernathy Fish Technology Center

**b) GAPS microsatellites**

| Description | Year | n | Life stage | Data source* |
|---|---|---|---|---|
| winter-run from Keswick | 1992 | 18 | adult | baseline (SWFSC) |
| winter-run from Keswick | 1993 | 4 | adult | baseline (SWFSC) |
| winter-run from Keswick | 1994 | 16 | adult | baseline (SWFSC) |
| winter-run from Keswick | 1995 | 17 | adult | baseline (SWFSC) |
| winter-run from Keswick | 1997 | 3 | adult | baseline (SWFSC) |
| winter-run from Keswick | 1998 | 17 | adult | baseline (SWFSC) |
| winter-run from Keswick | 2001 | 35 | adult | baseline (SWFSC) |
| winter-run from Keswick | 2002 | 101 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2003 | 9 | adult | baseline (SWFSC) |
| winter-run from Keswick | 2004 | 15 | adult | baseline (SWFSC) |
| winter-run from Keswick | 2007 | 156 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2008 | 198 | adult | rapid response (AFTC) |

*SWFSC = NOAA Fisheries Southwest Fisheries Science Center

**c) SWFSC SNPs**

| Description | Year | n | Life stage | Data source |
|---|---|---|---|---|
| winter-run from Keswick | 2002 | 47 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2003 | 47 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2009 | 47 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2010 | 47 | adult | rapid response (AFTC) |
| winter-run from Keswick | 2011 | 26 | adult | rapid response (AFTC) |

**d) HMSC microsatellites**

| Description | Year | n | Life stage | Data source* |
|---|---|---|---|---|
| winter-run from Keswick | 1991-1998 | 182 | adult | baseline (HMSC) |

*HMSC = Oregon State University Hatfield Marine Science Center

**Table 2 – Chinook salmon samples analyzed for comparison:**

**a) Rapid Response microsatellites**

| Description | H/W | Year | n | Life stage | Data source |
|---|---|---|---|---|---|
| Sacramento R. winter | mix | 1991-1998 | 187 | adult | baseline (UCD) |
| Butte Creek spring | mix | 1994-1998 | 184 | mix | baseline (UCD) |
| Mill and Deer Creek spring | mix | 1994-1998 | 188 | mix | baseline (UCD) |
| Sacramento R. fall 1[†] | mix | 1995 | 190 | adult | baseline (UCD) |
| Sacramento R. fall 2[†] | mix | 1993-1995 | 166 | adult | baseline (UCD) |

[†] The published baseline for Central Valley Chinook salmon [Ref 5] contains two groups of fall-run. The first (called "Fall 1" here) includes Nimbus Hatchery, Mokelumne River Hatchery, and Merced River Hatchery. The second (called "Fall 2" here) includes Coleman NFH, Battle Creek, Keswick Dam.

**b) GAPS microsatellites**

| Description | H/W | Year | n | Life stage | Data source |
|---|---|---|---|---|---|
| Battle Creek fall | H | 2002-2003 | 143 | adult | baseline (SWFSC) |
| Butte Creek fall | W | 2002 | 67 | adult | baseline (SWFSC) |
| Feather R. Hatchery fall | H | 2003 | 141 | adult | baseline (SWFSC) |
| Stanislaus River fall | W | 2002 | 76 | adult | baseline (SWFSC) |
| Butte Creek spring | W | 2002-2003 | 138 | adult | baseline (SWFSC) |
| Deer Creek spring | W | 2002 | 53 | adult | baseline (SWFSC) |
| Mill Creek spring | W | 2002-2003 | 91 | adult | baseline (SWFSC) |

### c) SWFSC SNPs

| Description | H/W | Year | n | Life stage | Data source |
|---|---|---|---|---|---|
| Feather R. Hatchery spring | H | 2006-2007 | 94 | adult | baseline (SWFSC) |
| Butte Creek spring | W | 2002-2005 | 430 | mix | baseline (SWFSC) |
| Mill Creek spring | W | 2002-2004 | 154 | mix | baseline (SWFSC) |
| Deer Creek spring | W | 2002-2005 | 120 | mix | baseline (SWFSC) |
| Feather R. Hatchery fall | H | 2002-2004 | 93 | adult | baseline (SWFSC) |
| Mill Creek fall | W | 2002-2004 | 97 | adult | baseline (SWFSC) |
| Deer Creek fall | W | 2002-2004 | 94 | adult | baseline (SWFSC) |
| Mokelumne R. fall | W | 2002-2004 | 95 | adult | baseline (SWFSC) |
| Battle Creek fall | H | 2002-2004 | 94 | adult | baseline (SWFSC) |
| Sacramento R. late fall | H | 2002-2004 | 93 | adult | baseline (SWFSC) |
| Sacramento R. winter | H | 1992-2003 | 108 | adult | baseline (SWFSC) |

### d) HMSC microsatellites

| Description | H/W | Year† | n | Life stage | Data source |
|---|---|---|---|---|---|
| Butte Creek spring | W | 1994-1998 | 179 | adult | baseline (HMSC) |
| Mill and Deer Creek spring | W | 1994-1998 | 159 | mix | baseline (HMSC) |
| Sacramento R. fall | H | 1993 | 189 | adult | baseline (HMSC) |
| Sacramento R. late fall | H | 1995 | 161 | adult | baseline (HMSC) |

† Samples from 2002-2005 have been run for these markers, and will be included in an upcoming version of the baseline.

**Genetic markers analyzed:**

1) Rapid Response microsatellites: 7 microsatellites standardized between UCD and AFTC [Ref 4, Ref 5].
2) GAPs microsatellites: 13 microsatellites standardized among most agency and academic laboratories, including HMSC, SWFSC and AFTC [Ref 5].
3) SWFSC SNPs: 94 single nucleotide polymorphism (SNP) markers developed by SWFSC and standardized with AFTC [Ref 5].
4) HMSC microsatellites: 16 microsatellites developed by HMSC and standardized with AFTC [Ref 6].

Complete lists of the markers in each of these sets are provided in Appendix 1. Genotyping success rates are presented in Appendix 2.

**Table 3 - Diversity within samples.** Expected ($H_e$) and observed ($H_o$) heterozygosity, allelic richness rank (AR rank, with 1 representing the most diversity and 19 representing the least diversity), number of loci exhibiting departures from Hardy-Weinberg Equilibrium (HWE), $F_{IS}$ (a measure of departure from random mating), number of pairs of loci exhibiting linkage disequilibrium (LD), and effective population size ($N_e$) based on LD are listed for each sample. Samples in which we observed no evidence for any disequilibrium caused by genetic drift due to a finite number of parents (i.e. those with an estimated $N_e$ of infinity) have $N_e$ marked by "-".

a) Rapid response microsatellites

| No | Description | $H_e$ | $H_o$ | AR rank | HWE | $F_{IS}$ | LD | $N_e$ |
|---|---|---|---|---|---|---|---|---|
| 1 | winter-run 1998 | 0.62 | 0.62 | 9 | 0 | -0.01 | 1 | 117 (37 - Infinite) |
| 2 | winter-run 1999 | 0.61 | 0.61 | 17 | 0 | 0.08 | 0 | - |
| 3 | winter-run 2000 | 0.60 | 0.60 | 18 | 1 | 0.07 | 0 | - |
| 4 | winter-run 2001 | 0.61 | 0.61 | 13 | 1 | 0.02 | 2 | 135 (72 - 348) |
| 5 | winter-run 2002 | 0.60 | 0.60 | 8 | 1 | -0.02 | 1 | 1,437 (152 - Infinite) |
| 6 | winter-run 2003 | 0.57 | 0.57 | 16 | 0 | -0.03 | 5 | - |
| 7 | winter-run 2004 | 0.60 | 0.60 | 7 | 2 | 0.02 | 12 | 98 (69 - 143) |
| 8 | winter-run 2005 | 0.60 | 0.60 | 5 | 1 | -0.01 | 9 | 161 (98 - 291) |
| 9 | winter-run 2006 | 0.58 | 0.58 | 12 | 2 | 0.02 | 2 | 126 (75 - 240) |
| 10 | winter-run 2007 | 0.60 | 0.60 | 15 | 0 | 0.03 | 4 | 108 (48 - 485) |
| 11 | winter-run 2008 | 0.61 | 0.61 | 11 | 1 | 0.03 | 2 | 100 (50 - 274) |
| 12 | winter-run 2009 | 0.58 | 0.58 | 19 | 0 | -0.04 | 2 | 412 (171 - Infinite) |
| 13 | winter-run 2010 | 0.60 | 0.60 | 9 | 1 | 0.00 | 20 | 55 (38 - 79) |
| 14 | winter-run 2011 | 0.58 | 0.58 | 13 | 2 | -0.04 | 14 | 67 (46 - 99) |
| | | | | | | | | |
| 15 | Sacramento R. winter | 0.61 | 0.61 | 6 | 0 | -0.02 | 3 | 173 (44 - Infinite) |
| 16 | Butte Creek spring | 0.76 | 0.76 | 4 | 0 | 0.01 | 1 | 228 (100 - 3874) |
| 17 | Mill and Deer Creek spring | 0.75 | 0.75 | 2 | 0 | 0.00 | 0 | - |
| 18 | Sacramento R. fall 1 | 0.76 | 0.76 | 1 | 0 | 0.03 | 0 | 901 (316 - Infinite) |
| 19 | Sacramento R. fall 2 | 0.71 | 0.71 | 3 | 2 | 0.00 | 5 | 444 (167 - Infinite) |

b) GAPS microsatellites

| No | Description | $H_e$ | $H_o$ | AR rank | HWE | $F_{IS}$ | LD | $N_e$ |
|---|---|---|---|---|---|---|---|---|
| 1 | winter-run 1992 | 0.68 | 0.68 | 17 | 2 | -0.06 | 6 | 7 (4 - 11) |
| 2 | winter-run 1993 | 0.63 | 0.64 | n/a | 0 | -0.06 | 0 | - |
| 3 | winter-run 1994 | 0.64 | 0.65 | 19 | 1 | -0.10 | 5 | 34 (13 - Infinite) |
| 4 | winter-run 1995 | 0.69 | 0.69 | 10 | 0 | -0.05 | 2 | 23 (12 - 94) |
| 5 | winter-run 1997 | 0.72 | 0.73 | 7 | 0 | 0.05 | 0 | - |
| 6 | winter-run 1998 | 0.71 | 0.71 | 11 | 1 | -0.04 | 1 | - |
| 7 | winter-run 2001 | 0.69 | 0.68 | 15 | 4 | 0.13 | 1 | 73 (33 - 3245) |
| 8 | winter-run 2002 | 0.68 | 0.68 | 15 | 2 | 0.01 | 8 | 971 (198 - Infinite) |
| 9 | winter-run 2003 | 0.63 | 0.66 | 13 | 0 | 0.09 | 0 | - |
| 10 | winter-run 2004 | 0.67 | 0.67 | 18 | 0 | 0.04 | 1 | - |
| 11 | winter-run 2007 | 0.69 | 0.69 | 13 | 3 | 0.02 | 20 | 279 (177 - 562) |
| 12 | winter-run 2008 | 0.71 | 0.71 | 9 | 0 | 0.02 | 7 | 1,546 (416 - Infinite) |
| | | | | | | | | |
| 13 | Battle Creek fall | 0.84 | 0.84 | 3 | 5 | 0.06 | 3 | - |
| 14 | Butte Creek fall | 0.83 | 0.83 | 4 | 1 | 0.01 | 4 | 5,564 (241 - Infinite) |
| 15 | Feather R. Hatchery fall | 0.85 | 0.85 | 2 | 5 | 0.02 | 5 | 1,147 (337 - Infinite) |
| 16 | Stanislaus River fall | 0.85 | 0.85 | 1 | 0 | -0.02 | 2 | - |
| 17 | Butte Creek spring | 0.79 | 0.79 | 8 | 1 | 0.03 | 0 | 1,526 (292 - Infinite) |
| 18 | Deer Creek spring | 0.83 | 0.83 | 5 | 2 | 0.04 | 4 | 164 (87 - 779) |
| 19 | Mill Creek spring | 0.83 | 0.83 | 6 | 7 | 0.04 | 26 | 105 (75 - 162) |

c) SWFSC SNPs

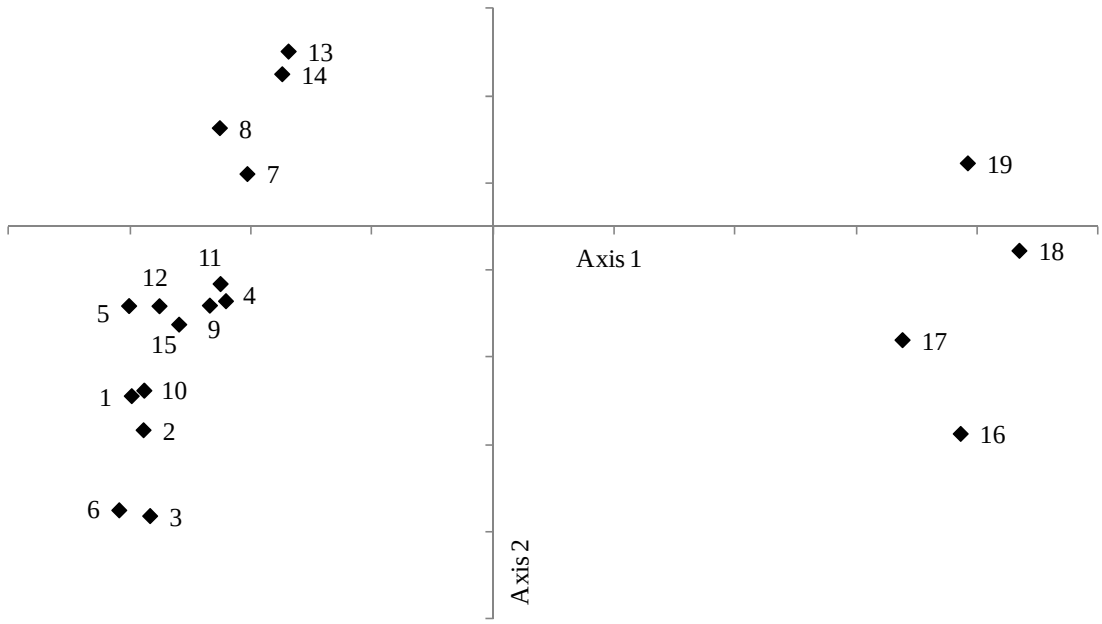
| No | Description | $H_e$ | $H_o$ | AR rank | HWE | $F_{IS}$ | LD | $N_e$ |
|---|---|---|---|---|---|---|---|---|
| 1 | winter-run 2002 | 0.30 | 0.30 | 12 | 4 | 0.02 | 175 | 93 (66 - 149) |
| 2 | winter-run 2003 | 0.30 | 0.30 | 14 | 1 | -0.01 | 145 | 182 (106 - 535) |
| 3 | winter-run 2009 | 0.30 | 0.3 | 15 | 3 | 0.04 | 152 | 279 (131 - Infinite) |
| 4 | winter-run 2010 | 0.30 | 0.30 | 16 | 2 | -0.01 | 161 | 77 (57 - 113) |
| 5 | winter-run 2011 | 0.30 | 0.30 | 11 | 1 | 0.02 | 130 | 79 (49 - 179) |
| | | | | | | | | |
| 6 | Feather R. Hatchery spring | 0.39 | 0.39 | 2 | 3 | -0.02 | 182 | - |
| 7 | Butte Creek spring | 0.36 | 0.36 | 8 | 20 | 0.11 | 224 | 568 (323 – 1,889) |
| 8 | Mill Creek spring | 0.38 | 0.38 | 1 | 4 | 0.00 | 539 | 62 (54 - 72) |
| 9 | Deer Creek spring | 0.37 | 0.37 | 3 | 2 | 0.06 | 279 | 212 (148 - 351) |
| 10 | Feather R. Hatchery fall | 0.38 | 0.38 | 7 | 4 | 0.00 | 188 | 1,674 (487 - Infinite) |
| 11 | Mill Creek fall | 0.37 | 0.37 | 9 | 0 | 0.02 | 182 | 2,332 (523 - Infinite) |
| 12 | Deer Creek fall | 0.37 | 0.37 | 6 | 4 | 0.03 | 211 | 628 (317 – 7,492) |
| 13 | Mokelumne R. fall | 0.37 | 0.37 | 5 | 6 | -0.01 | 194 | 610 (318 – 4,268) |
| 14 | Battle Creek fall | 0.37 | 0.37 | 4 | 9 | 0.07 | 225 | 696 (307 - Infinite) |
| 15 | Sacramento R. late-fall | 0.37 | 0.37 | 9 | 6 | 0.01 | 184 | 1,339 (439 - Infinite) |
| 16 | Sacramento R. winter | 0.30 | 0.30 | 13 | 9 | 0.07 | 298 | 95 (78 - 118) |

d) HMSC microsatellites

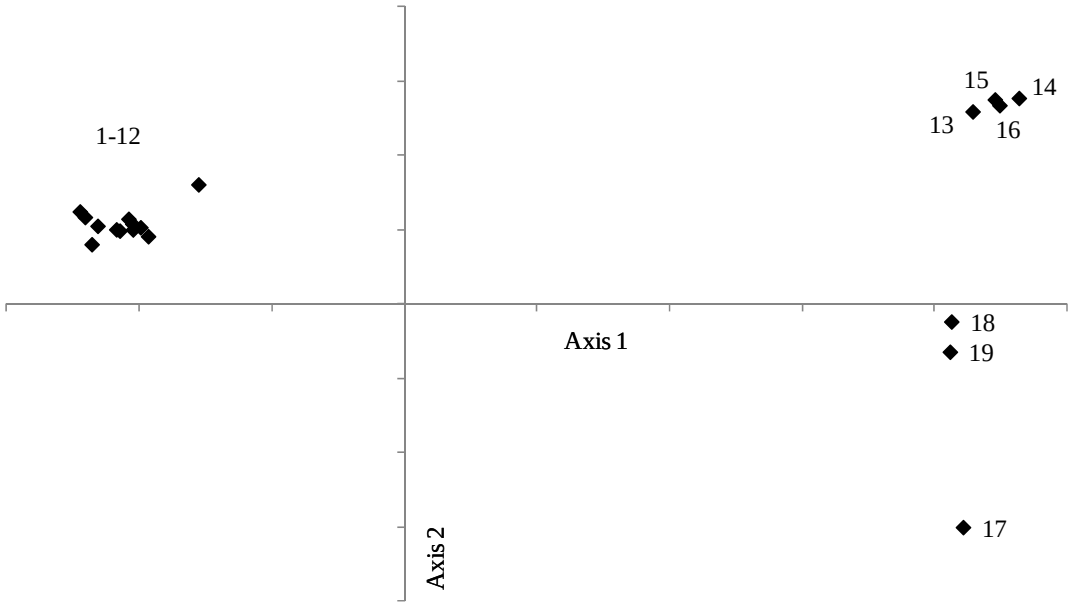
| No | Description | $H_e$ | $H_o$ | AR rank | HWE | $F_{IS}$ | LD | $N_e$ |
|---|---|---|---|---|---|---|---|---|
| 1 | Sacramento R. winter | 0.78 | 0.78 | 5 | 4 | 0.03 | 6 | 2,506 (612 - Infinite) |
| | | | | | | | | |
| 2 | Butte Creek spring | 0.90 | 0.90 | 4 | 6 | 0.06 | 19 | 705 (365 - 4,632) |
| 3 | Mill and Deer Creek spring | 0.93 | 0.93 | 2 | 11 | 0.06 | 32 | 167 (137 - 209) |
| 4 | Sacramento R. fall | 0.94 | 0.94 | 1 | 12 | 0.11 | 12 | 5,360 (987 - Infinite) |
| 5 | Sacramento R. late fall | 0.92 | 0.92 | 3 | 14 | 0.17 | 26 | 438 (259 - 1,207) |

**Figure 1 - Correspondence Analysis (CA) of allele frequencies observed in winter-run from Keswick Dam and baseline Chinook salmon collections.** Data labels correspond to Table 3.

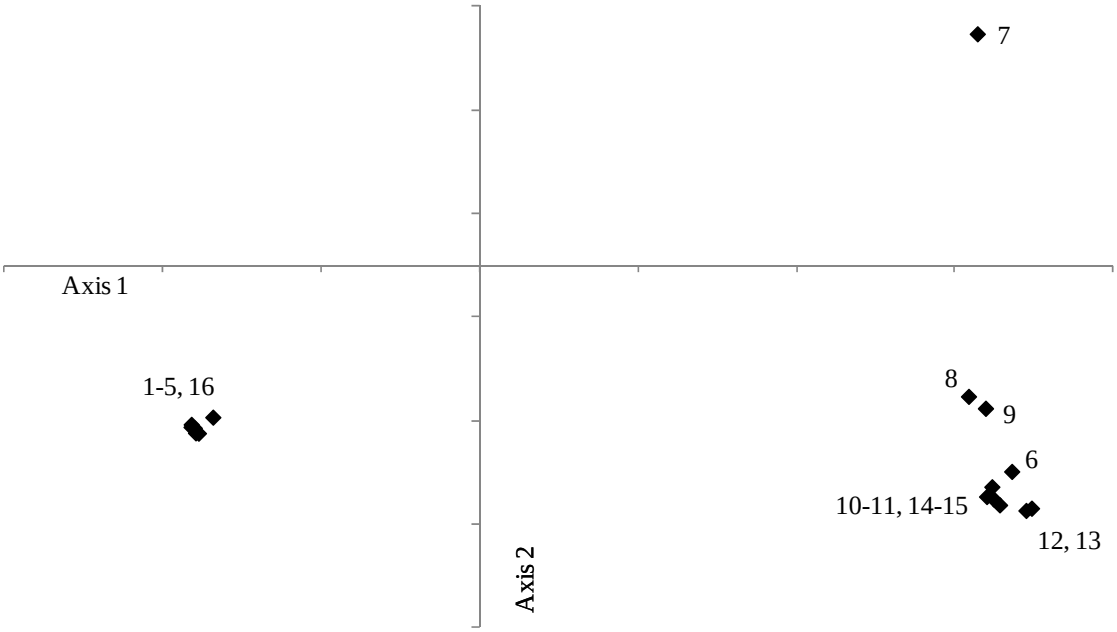
a) Rapid Response microsatellites. Axis 1 and Axis 2 account for 44% and 13% of the variance, respectively.




a) GAPS microsatellites. Axis 1 and Axis 2 account for 56% and 14% of the variance, respectively.



b) SWFSC SNPs. Axis 1 and Axis 2 account for 62% and 21% of the variance, respectively.




c) HMSC microsatellites. Axis 1 and Axis 2 account for 49% and 27% of the variance, respectively.

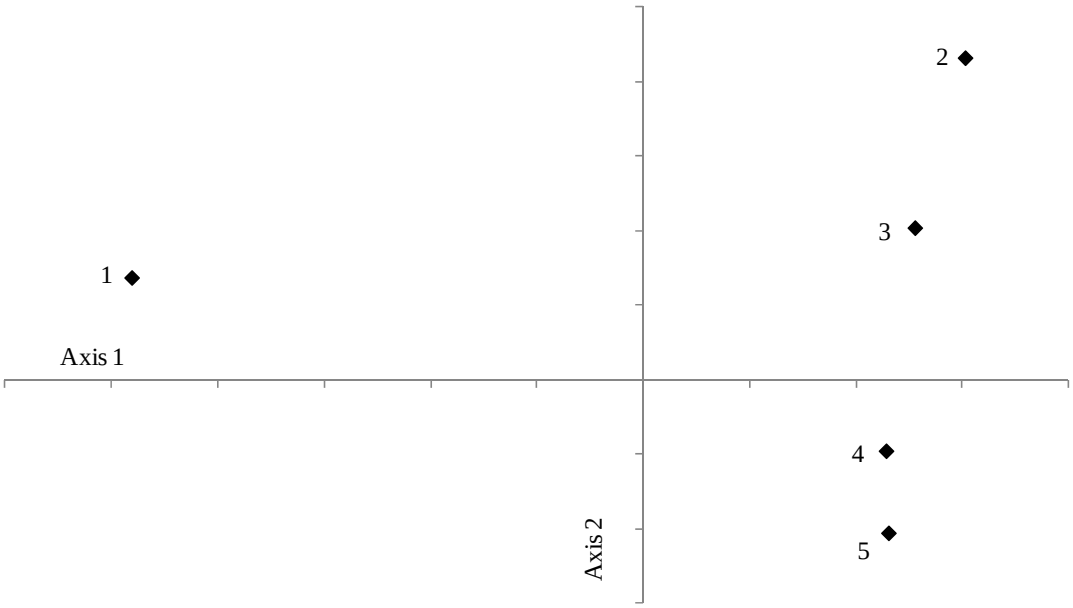
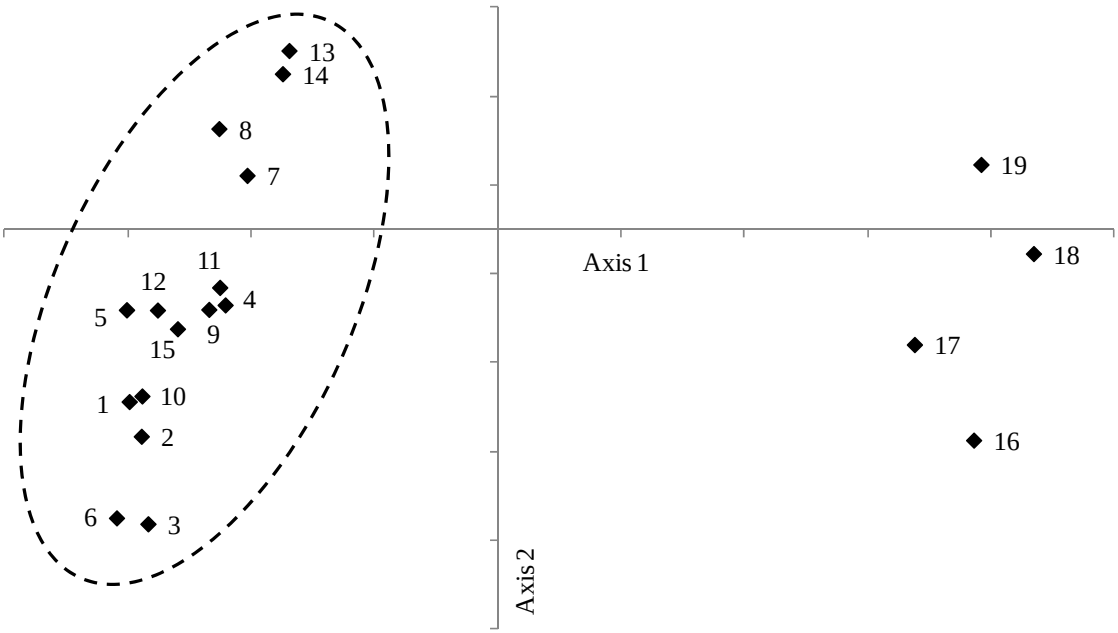
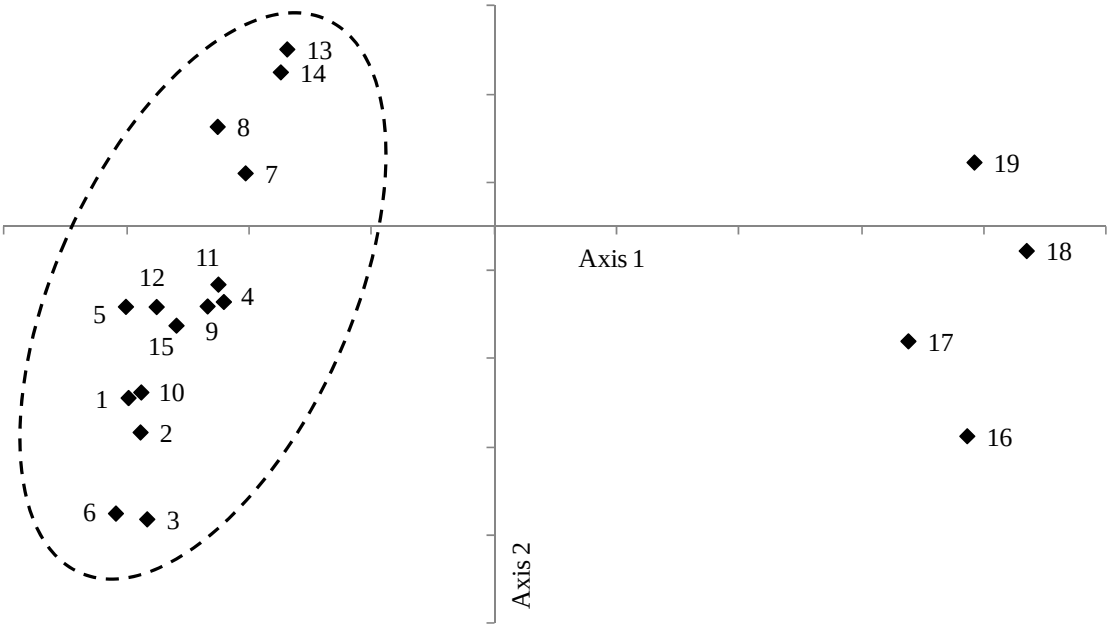


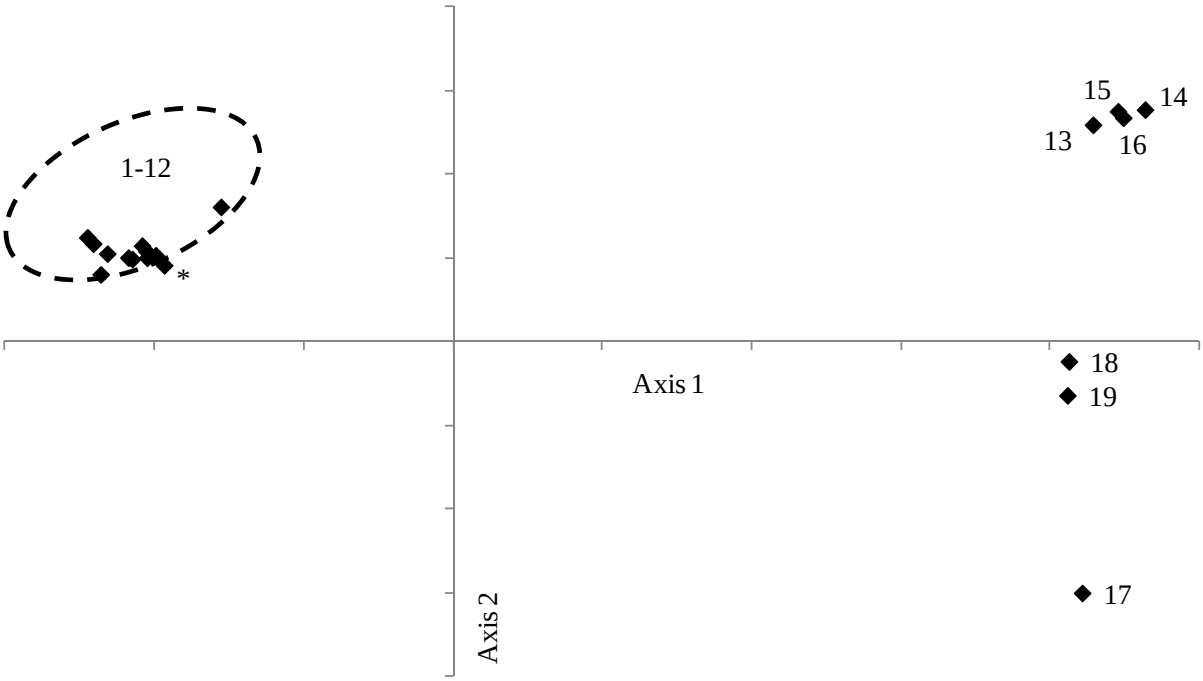
**Figure 2 - Statistical tests of divergence among winter-run from Keswick Dam and baseline Chinook salmon collections.** Data labels correspond to Table 3. Dashed lines indicate groups of samples lacking statistically different allele frequencies (top) and statistically significant $F_{ST}$ values (bottom).

a) Rapid Response Microsatellites

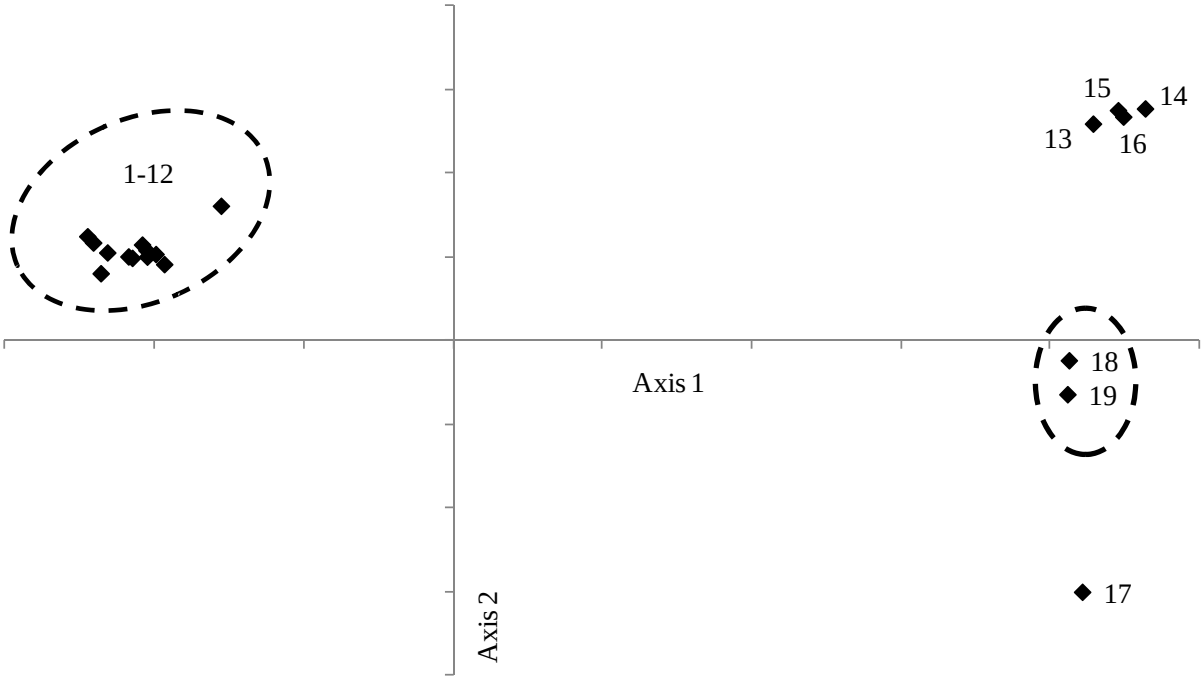


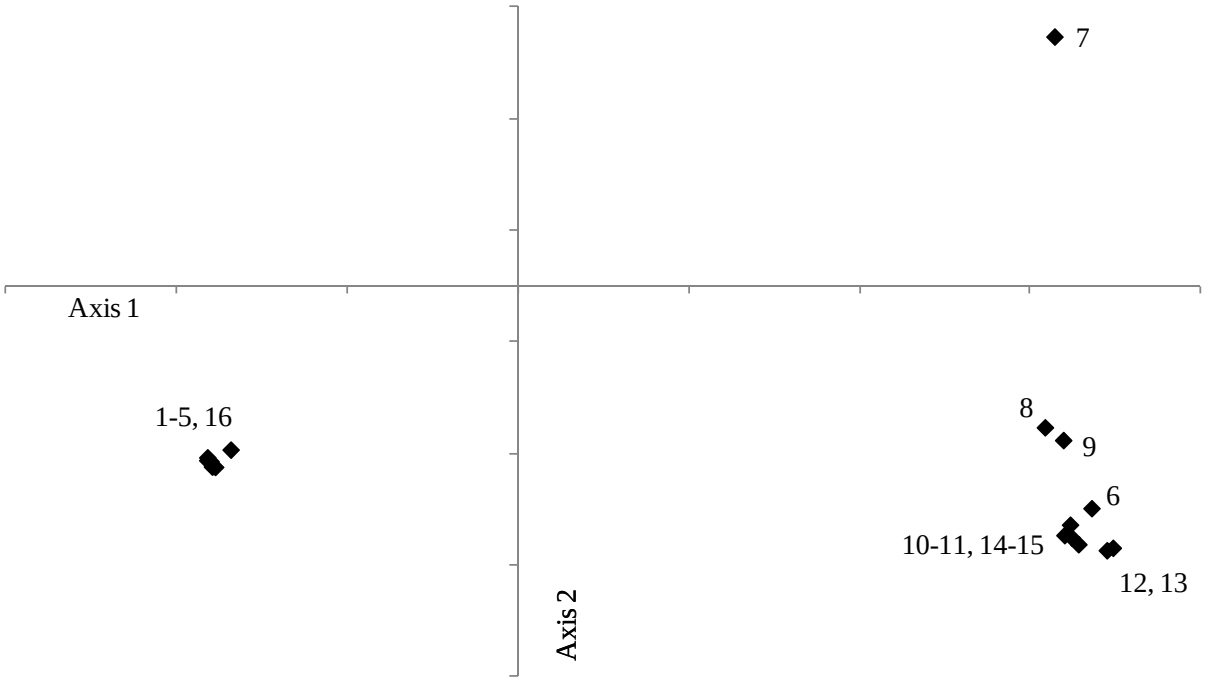
b) GAPS microsatellites

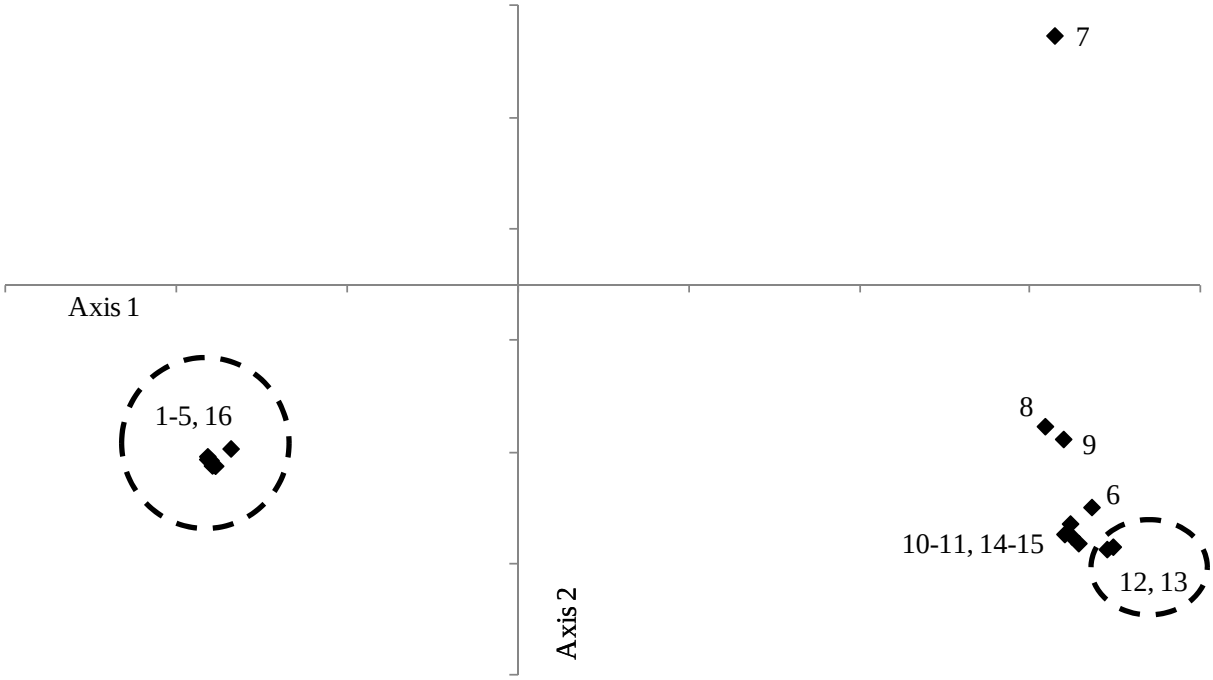



*1992 sample

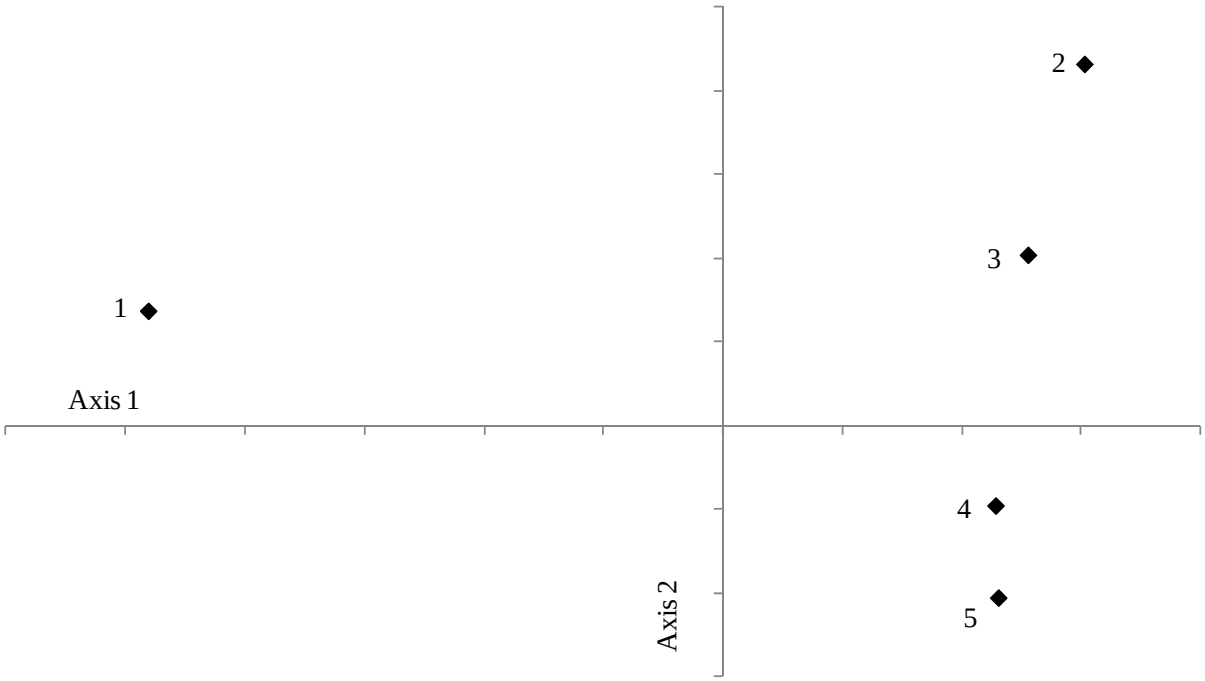


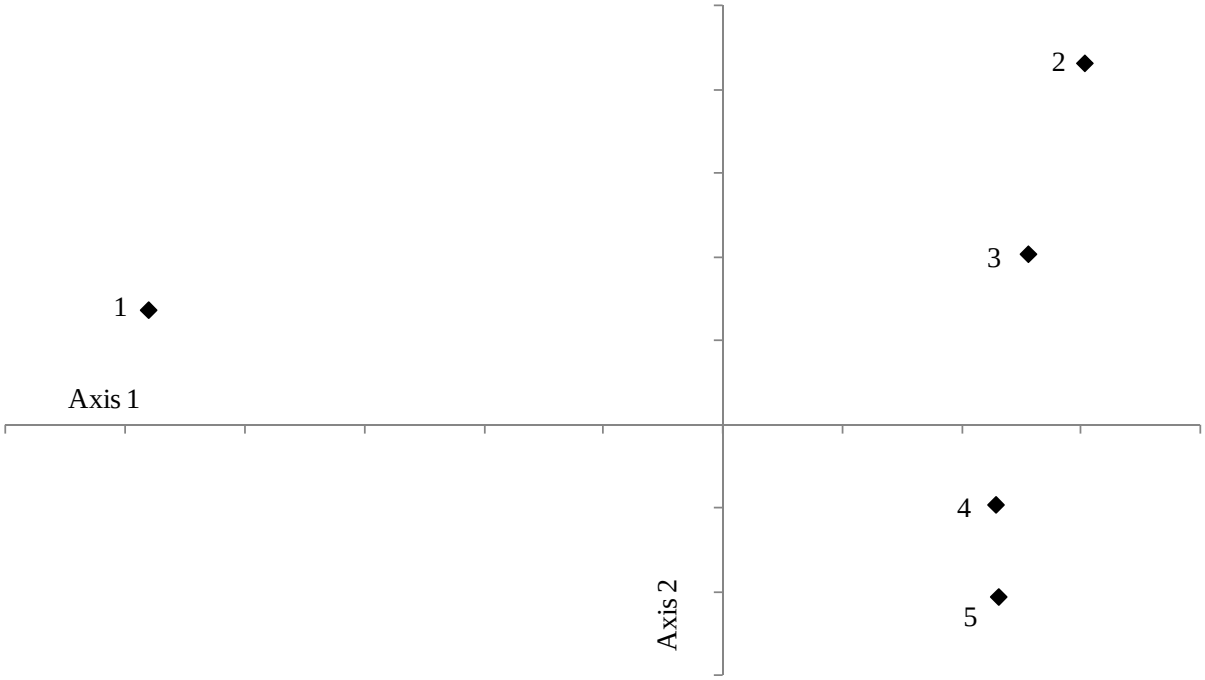
c) SWFSC SNPs


7
Axis 1
1-5, 16
8
9
6
10-11, 14-15
12, 13
Axis 2


7
Axis 1
1-5, 16
8
9
6
10-11, 14-15
12, 13
Axis 2

d) HMSC microsatellites



**Comments**

- The goals of this report series are 1) to summarize available genetic information for NFH broodstocks and make that information available to hatchery managers, and 2) to make sure that data for the NFH broodstocks are available for internal hatchery reviews and HET meetings, as well as to our partners.
- Genetic diversity (measured by heterozygosity and allelic richness) was generally low in the winter-run samples relative to other runs of Central Valley Chinook salmon. This pattern was reflected in all four marker sets. These results are consistent with the fact that the winter-run population went through a substantial bottleneck in the recent past.
- Correspondence analysis of each data set revealed that the primary source of divergence among Central Valley Chinook salmon (indicated by the x-axis in Figure 2) reflected divergence between the winter-run population and all other populations. These results emphasize the distinctiveness of the winter-run population relative to all other Central Valley Chinook salmon populations.
- Tests for significance of genetic divergence revealed that all winter-run samples were significantly divergent from all non-winter-run samples. Some comparisons among winter-run samples were significant, but many were not (Figure 2, Appendix 3).

**Sources cited**

1. USFWS. 2011. Biological Assessment of Artificial Propagation at Coleman National Fish Hatchery and Livingston Stone National Fish Hatchery: program description and incidental take of Chinook salmon and steelhead. Available at http://www.fws.gov/redbluff/he_reports.aspx

2. Robert Null. Red Bluff Fish and Wildlife Office. pers comm.

3. USFWS. 2011. Pre-release Report for brood year 2010 winter Chinook salmon juveniles propagated at the U.S. Fish and Wildlife Service's Livingston Stone National Fish Hatchery.

4. Abernathy Fish Technology Center Standard Operating Procedure #21- *Sacramento River Chinook Salmon Rapid Response*. Developed based on Banks et al. 2000; available upon request.

5. Information regarding the markers and the baselines in which they are used are available:

a) Rapid Response microsatellites

Banks, M. A., V. K. Rashbrook, M. J. Calavetta, C. A. Dean, and D. Hedgecock. 2000. Analysis of microsatellite DNA resolves genetic structure and diversity of chinook salmon (*Oncorhynchus tshawytscha*) in California's Central Valley. Canadian Journal of Fisheries & Aquatic Sciences 57(5):915-927.

b) GAPS microsatellites

Seeb, L. W., A. Antonovich, A. A. Banks, T. D. Beacham, A. R. Bellinger, S. M. Blankenship, A. R. Campbell, N. A. Decovich, J. C. Garza, C. M. Guthrie, T. A. Lundrigan, P. Moran, S. R. Narum, J. J. Stephenson, K. J. Supernault, D. J. Teel, W. D. Templin, J. K. Wenburg, S. E. Young, and C. T. Smith. 2007. Development of a standardized DNA database for Chinook salmon. Fisheries 32(11):540-552.

c) SWFSC SNPs

J. Carlos Garza. Southwest Fisheries Science Center, NOAA Fisheries. pers comm..

d) HMSC microsatellites

M. Banks. Hatfield Marine Science Center, Oregon State University

6. Smith, C. T., A. R. LaGrange, W. R. Ardren, M. A. Banks, and D. P. Jacobson. 2008. Run composition of Chinook salmon at Red Bluff Diversion Dam during gates-in operations: A comparison of phenotypic and genetic assignment to run type. U. S. Fish and Wildlife Service, Abernathy Fish Technology Center Report.

## Availability

Genotype data and allele frequencies for NFH stocks are available from Abernathy Fish Technology Center upon request. Data collected by our partners are available from the sources listed above.

## Disclaimer

The findings and conclusions in this report are those of the author and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

**Appendix 1.** Genetic markers used to analyze Livingston Stone NFH Chinook salmon.

a) Rapid Response microsatellites

| | Microsatellite markers |
|---|---|
| 1 | Ots2 |
| 2 | Ots3 |
| 3 | Ots9 |
| 4 | Ots10 |
| 5 | One13 |
| 6 | Ot104 |
| 7 | Ot107 |

b) GAPS microsatellites

| | Microsatellite markers |
|---|---|
| 1 | Ogo2 |
| 2 | Ogo4 |
| 3 | Oki100 |
| 4 | Omm1080 |
| 5 | Ots201b |
| 6 | Ots208b |
| 7 | Ots211 |
| 8 | Ots212 |
| 9 | Ots213 |
| 10 | Ots3M |
| 11 | Ots9 |
| 12 | OtsG474 |
| 13 | Ssa408 |

c) SWFSC SNPs

| SNP markers | | | | | |
|---|---|---|---|---|---|
| 1 | AldB1-122 | 33 | Ots_110551-64 | 65 | Ots_96222-525 |
| 2 | AldoB4-183 | 34 | Ots_110689-218 | 66 | Ots_96500-180 |
| 3 | Myc-366 | 35 | Ots_111666-408 | 67 | Ots_97077-179 |
| 4 | OTALDBINT1-SNP1 | 36 | Ots_111681-657 | 68 | Ots_99550-204 |
| 5 | OTNAML12_1-SNP1 | 37 | Ots_112208-722 | 69 | Ots_ARNT-195 |
| 6 | Ots_100884-287 | 38 | Ots_112301-43 | 70 | Ots_AsnRS-60 |
| 7 | Ots_101119-381 | 39 | Ots_112419-131 | 71 | Ots_aspat-196 |
| 8 | Ots_101704-143 | 40 | Ots_112820-284 | 72 | Ots_CD59-2 |
| 9 | Ots_102213-210 | 41 | Ots_112876-371 | 73 | Ots_CD63 |
| 10 | Ots_102414-395 | 42 | Ots_113242-216 | 74 | Ots_EP-529 |
| 11 | Ots_102420-494 | 43 | Ots_113457-40 | 75 | Ots_GDH-81x |
| 12 | Ots_102457-132 | 44 | Ots_117043-255 | 76 | Ots_HSP90B-385 |
| 13 | Ots_102801-308 | 45 | Ots_117242-136 | 77 | Ots_MHC1 |
| 14 | Ots_103041-52 | 46 | Ots_117432-409 | 78 | Ots_mybp-85 |
| 15 | Ots_104063-132 | 47 | Ots_118175-479 | 79 | Ots_myoD-364 |
| 16 | Ots_104569-86 | 48 | Ots_118205-61 | 80 | Ots_Ots311-101x |
| 17 | Ots_105105-613 | 49 | Ots_118938-325 | 81 | Ots_PGK-54 |
| 18 | Ots_105132-200 | 50 | Ots_122414-56 | 82 | Ots_Prl2 |
| 19 | Ots_105401-325 | 51 | Ots_123048-521 | 83 | Ots_RAG3 |
| 20 | Ots_105407-117 | 52 | Ots_123921-111 | 84 | Ots_RFC2-558 |
| 21 | Ots_106499-70 | 53 | Ots_124774-477 | 85 | Ots_SClkF2R2-135 |
| 22 | Ots_106747-239 | 54 | Ots_127236-62 | 86 | Ots_SWS1op-182 |
| 23 | Ots_107074-284 | 55 | Ots_128302-57 | 87 | Ots_TAPBP |
| 24 | Ots_107285-93 | 56 | Ots_128693-461 | 88 | Ots_U07-07.161 |
| 25 | Ots_107806-821 | 57 | Ots_128757-61 | 89 | Ots_u07-49.290 |
| 26 | Ots_108007-208 | 58 | Ots_129144-472 | 90 | Ots_U4-92 |
| 27 | Ots_108390-329 | 59 | Ots_129170-683 | 91 | OTSBMP-2-SNP1 |
| 28 | Ots_108735-302 | 60 | Ots_129458-451 | 92 | OTSTF1-SNP1 |
| 29 | Ots_109693-392 | 61 | Ots_130720-99 | 93 | S71-336 |
| 30 | Ots_110064-383 | 62 | Ots_131460-584 | 94 | unk_526 |
| 31 | Ots_110201-363 | 63 | Ots_131906-141 | | |
| 32 | Ots_110495-380 | 64 | Ots_94857-232 | | |

d) HMSC microsatellites

| Microsatellite markers | |
|---|---|
| 1 | Ots104 |
| 2 | Ots107 |
| 3 | Ots201b |
| 4 | Ots208b |
| 5 | Ots209 |
| 6 | Ots211 |
| 7 | Ots212 |
| 8 | Ots215 |
| 9 | Ots249 |
| 10 | Ots253b |
| 11 | Ots515 |
| 12 | OtsG311 |
| 13 | OtsG409 |
| 14 | OtsG422 |
| 15 | OtsG78b |
| 16 | OtsG83b |

**Appendix 2.** Completeness of data as received or generated for this report. Shaded cells indicate data that are <90% complete.

a) Rapid Response microsatellites

| Description | Year | Microsatellite call rate |
|---|---|---|
| winter-run from Keswick | 1998 | 0.977 |
| winter-run from Keswick | 1999 | 0.963 |
| winter-run from Keswick | 2000 | 0.734 |
| winter-run from Keswick | 2001 | 0.963 |
| winter-run from Keswick | 2002 | 0.970 |
| winter-run from Keswick | 2003 | 0.764 |
| winter-run from Keswick | 2004 | 0.999 |
| winter-run from Keswick | 2005 | 0.999 |
| winter-run from Keswick | 2006 | 0.981 |
| winter-run from Keswick | 2007 | 0.994 |
| winter-run from Keswick | 2008 | 0.984 |
| winter-run from Keswick | 2009 | 0.999 |
| winter-run from Keswick | 2010 | 0.993 |
| winter-run from Keswick | 2011 | 0.996 |
| | | |
| Sacramento R. winter | 1991-1998 | 0.978 |
| Butte Creek spring | 1994-1998 | 0.916 |
| Mill and Deer Creek spring | 1994-1998 | 0.859 |
| Sacramento R. fall 1 | 1995 | 0.962 |
| Sacramento R. fall 2 | 1993-1995 | 0.924 |

b) GAPS microsatellites

| Description | Year | Microsatellite call rate |
|---|---|---|
| winter-run from Keswick | 1992 | 0.949 |
| winter-run from Keswick | 1993 | 0.808 |
| winter-run from Keswick | 1994 | 0.870 |
| winter-run from Keswick | 1995 | 0.910 |
| winter-run from Keswick | 1997 | 0.795 |
| winter-run from Keswick | 1998 | 0.833 |
| winter-run from Keswick | 2001 | 0.840 |
| winter-run from Keswick | 2002 | 0.997 |
| winter-run from Keswick | 2003 | 0.700 |
| winter-run from Keswick | 2004 | 0.821 |
| winter-run from Keswick | 2007 | 0.999 |
| winter-run from Keswick | 2008 | 0.999 |
| | | |
| Battle Creek fall | 2002-2003 | 0.855 |
| Butte Creek fall | 2002 | 0.937 |
| Feather River H. fall | 2003 | 0.921 |
| Stanislaus River fall | 2002 | 0.881 |
| Butte Creek spring | 2002-2003 | 0.847 |
| Deer Creek spring | 2002 | 0.903 |
| Mill Creek spring | 2002-2003 | 0.907 |

c) SWFSC SNPs

| Description | Year | SNP call rate |
|---|---|---|
| winter-run from Keswick | 2002 | 0.999 |
| winter-run from Keswick | 2003 | 0.999 |
| winter-run from Keswick | 2009 | 0.999 |
| winter-run from Keswick | 2010 | 0.998 |
| winter-run from Keswick | 2011 | 0.988 |
| | | |
| Feather River H. spring | 2006-2007 | 0.968 |
| Butte Creek spring | 2002-2005 | 0.911 |
| Mill Creek spring | 2002-2004 | 0.969 |
| Deer Creek spring | 2002-2005 | 0.906 |
| Feather River H. fall | 2002-2004 | 0.997 |
| Mill Creek fall | 2002-2004 | 0.970 |
| Deer Creek fall | 2002-2004 | 0.969 |
| Mokelumne River fall | 2002-2004 | 0.998 |
| Battle Creek fall | 2002-2004 | 0.916 |
| Sacramento River late fall | 2002-2004 | 0.984 |
| Sacramento River winter | 1992-2003 | 0.920 |

d) HMSC microsatellites

| Description | Year | Microsatellite call rate |
|---|---|---|
| winter-run from Keswick | 1991-1998 | 0.963 |
| | | |
| Butte Creek spring | 1994-1998 | 0.934 |
| Mill and Deer Creek spring | 1994-1998 | 0.882 |
| Sacramento R. fall | 1995 | 0.951 |
| Sacramento R. late fall | 1993-1995 | 0.806 |

**Appendix 3.** Pairwise $F_{ST}$ values between collections of Chinook salmon. Sample numbers are those listed in Table 3. Shaded cells indicate non-significant results (pairwise $F_{ST}$ values not >95% of a null distribution in which individuals were permuted among samples).

a) Rapid Response microsatellites

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | 0.005 | -0.002 | 0.000 | 0.003 | 0.006 | 0.005 | 0.005 | 0.008 | 0.002 | 0.000 | 0.004 | 0.004 | 0.010 | -0.001 | 0.165 | 0.156 | 0.156 | 0.185 |
| 2 | | - | -0.011 | -0.007 | -0.005 | -0.004 | 0.000 | -0.001 | 0.000 | -0.005 | -0.007 | -0.005 | -0.003 | 0.000 | -0.005 | 0.164 | 0.155 | 0.154 | 0.189 |
| 3 | | | - | -0.007 | -0.007 | -0.003 | -0.006 | -0.003 | 0.001 | -0.006 | -0.008 | -0.004 | -0.007 | -0.001 | -0.004 | 0.175 | 0.161 | 0.161 | 0.187 |
| 4 | | | | - | 0.001 | 0.003 | 0.002 | 0.004 | 0.007 | 0.001 | 0.000 | 0.002 | 0.003 | 0.005 | 0.001 | 0.182 | 0.171 | 0.171 | 0.199 |
| 5 | | | | | - | 0.001 | 0.001 | 0.000 | 0.005 | 0.000 | -0.001 | 0.001 | 0.000 | 0.004 | 0.000 | 0.182 | 0.168 | 0.170 | 0.198 |
| 6 | | | | | | - | 0.002 | 0.006 | 0.000 | 0.002 | 0.000 | -0.002 | 0.004 | 0.001 | 0.003 | 0.193 | 0.182 | 0.182 | 0.212 |
| 7 | | | | | | | - | 0.003 | 0.006 | 0.000 | 0.001 | 0.002 | 0.003 | 0.005 | 0.002 | 0.191 | 0.178 | 0.179 | 0.205 |
| 8 | | | | | | | | - | 0.007 | 0.002 | 0.003 | 0.003 | 0.003 | 0.008 | 0.002 | 0.188 | 0.173 | 0.174 | 0.200 |
| 9 | | | | | | | | | - | 0.005 | 0.005 | 0.002 | 0.007 | 0.008 | 0.007 | 0.194 | 0.178 | 0.180 | 0.205 |
| 10 | | | | | | | | | | - | 0.000 | 0.001 | 0.001 | 0.005 | 0.000 | 0.177 | 0.167 | 0.167 | 0.197 |
| 11 | | | | | | | | | | | - | 0.001 | 0.000 | 0.003 | -0.001 | 0.181 | 0.170 | 0.170 | 0.200 |
| 12 | | | | | | | | | | | | - | 0.003 | 0.003 | 0.002 | 0.197 | 0.185 | 0.185 | 0.213 |
| 13 | | | | | | | | | | | | | - | 0.004 | 0.002 | 0.187 | 0.173 | 0.173 | 0.201 |
| 14 | | | | | | | | | | | | | | - | 0.006 | 0.209 | 0.195 | 0.196 | 0.224 |
| 15 | | | | | | | | | | | | | | | - | 0.171 | 0.160 | 0.161 | 0.190 |
| 16 | | | | | | | | | | | | | | | | - | 0.020 | 0.030 | 0.059 |
| 17 | | | | | | | | | | | | | | | | | - | 0.014 | 0.025 |
| 18 | | | | | | | | | | | | | | | | | | - | 0.016 |
| 19 | | | | | | | | | | | | | | | | | | | - |

b) GAPS microsatellites

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | 0.072 | 0.059 | 0.052 | 0.035 | 0.039 | 0.048 | 0.043 | 0.070 | 0.056 | 0.041 | 0.040 | 0.119 | 0.135 | 0.116 | 0.119 | 0.133 | 0.122 | 0.119 |
| 2 | | - | 0.023 | 0.004 | 0.009 | 0.041 | 0.002 | 0.003 | 0.028 | 0.045 | 0.002 | 0.001 | 0.126 | 0.140 | 0.128 | 0.131 | 0.154 | 0.139 | 0.132 |
| 3 | | | - | 0.055 | 0.023 | 0.032 | 0.024 | 0.017 | 0.059 | 0.039 | 0.018 | 0.026 | 0.142 | 0.162 | 0.143 | 0.145 | 0.156 | 0.147 | 0.145 |
| 4 | | | | - | 0.002 | 0.025 | 0.019 | 0.017 | 0.034 | 0.029 | 0.012 | 0.012 | 0.131 | 0.149 | 0.133 | 0.134 | 0.158 | 0.145 | 0.138 |
| 5 | | | | | - | 0.020 | -0.020 | -0.002 | 0.022 | -0.001 | 0.005 | 0.000 | 0.084 | 0.102 | 0.090 | 0.099 | 0.119 | 0.098 | 0.102 |
| 6 | | | | | | - | 0.001 | 0.006 | 0.033 | 0.014 | 0.006 | 0.006 | 0.115 | 0.134 | 0.116 | 0.118 | 0.128 | 0.124 | 0.121 |
| 7 | | | | | | | - | 0.005 | 0.009 | 0.011 | 0.009 | 0.004 | 0.131 | 0.152 | 0.134 | 0.136 | 0.146 | 0.142 | 0.138 |
| 8 | | | | | | | | - | 0.009 | 0.005 | 0.001 | 0.001 | 0.131 | 0.153 | 0.133 | 0.138 | 0.150 | 0.144 | 0.138 |
| 9 | | | | | | | | | - | 0.005 | 0.019 | 0.015 | 0.135 | 0.152 | 0.138 | 0.141 | 0.158 | 0.139 | 0.142 |
| 10 | | | | | | | | | | - | 0.005 | 0.008 | 0.117 | 0.139 | 0.122 | 0.124 | 0.142 | 0.131 | 0.123 |
| 11 | | | | | | | | | | | - | 0.001 | 0.126 | 0.147 | 0.128 | 0.132 | 0.142 | 0.137 | 0.131 |
| 12 | | | | | | | | | | | | - | 0.120 | 0.141 | 0.123 | 0.126 | 0.137 | 0.132 | 0.127 |
| 13 | | | | | | | | | | | | | - | 0.003 | 0.002 | 0.002 | 0.028 | 0.014 | 0.013 |
| 14 | | | | | | | | | | | | | | - | 0.002 | 0.003 | 0.035 | 0.016 | 0.017 |
| 15 | | | | | | | | | | | | | | | - | 0.002 | 0.030 | 0.013 | 0.013 |
| 16 | | | | | | | | | | | | | | | | - | 0.026 | 0.014 | 0.012 |
| 17 | | | | | | | | | | | | | | | | | - | 0.025 | 0.020 |
| 18 | | | | | | | | | | | | | | | | | | - | 0.002 |
| 19 | | | | | | | | | | | | | | | | | | | - |

c) SWFSC SNPs

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | - | 0.002 | 0.004 | 0.010 | 0.004 | 0.137 | 0.134 | 0.128 | 0.131 | 0.130 | 0.134 | 0.143 | 0.142 | 0.131 | 0.131 | 0.004 |
| 2 | | - | -0.001 | 0.003 | 0.002 | 0.138 | 0.143 | 0.133 | 0.138 | 0.131 | 0.137 | 0.144 | 0.144 | 0.133 | 0.132 | 0.002 |
| 3 | | | - | 0.008 | 0.004 | 0.139 | 0.143 | 0.135 | 0.139 | 0.131 | 0.138 | 0.142 | 0.144 | 0.134 | 0.134 | 0.002 |
| 4 | | | | - | 0.006 | 0.138 | 0.144 | 0.134 | 0.139 | 0.133 | 0.137 | 0.148 | 0.147 | 0.135 | 0.135 | 0.007 |
| 5 | | | | | - | 0.135 | 0.143 | 0.129 | 0.138 | 0.131 | 0.136 | 0.146 | 0.144 | 0.132 | 0.135 | 0.004 |
| 6 | | | | | | - | 0.038 | 0.018 | 0.020 | 0.006 | 0.012 | 0.013 | 0.014 | 0.010 | 0.019 | 0.147 |
| 7 | | | | | | | - | 0.021 | 0.025 | 0.036 | 0.042 | 0.043 | 0.045 | 0.040 | 0.042 | 0.148 |
| 8 | | | | | | | | - | 0.007 | 0.019 | 0.024 | 0.029 | 0.031 | 0.018 | 0.025 | 0.140 |
| 9 | | | | | | | | | - | 0.017 | 0.020 | 0.025 | 0.029 | 0.019 | 0.025 | 0.143 |
| 10 | | | | | | | | | | - | 0.003 | 0.003 | 0.004 | 0.003 | 0.009 | 0.139 |
| 11 | | | | | | | | | | | - | 0.002 | 0.003 | 0.000 | 0.009 | 0.145 |
| 12 | | | | | | | | | | | | - | 0.000 | 0.003 | 0.009 | 0.153 |
| 13 | | | | | | | | | | | | | - | 0.005 | 0.010 | 0.151 |
| 14 | | | | | | | | | | | | | | - | 0.010 | 0.142 |
| 15 | | | | | | | | | | | | | | | - | 0.141 |
| 16 | | | | | | | | | | | | | | | | - |

d) HMSC microsatellites

| | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | - | 0.109 | 0.089 | 0.090 | 0.098 |
| 2 | | - | 0.021 | 0.029 | 0.039 |
| 3 | | | - | 0.014 | 0.023 |
| 4 | | | | - | 0.008 |
| 5 | | | | | - |

**Appendix 4.** Glossary

**Allele** – A unique genetic character state. Each locus has two alleles.

**Allelic richness** – The number of alleles observed in a sample of individuals, corrected for unequal sample sizes by rarefaction.

**Effective population size ($N_e$)** – The number of individuals in a model population which would lose genetic variation at the same rate as an observed population. Deviations from model behavior in real populations (e.g. unequal sex ratios, some individuals reproducing more than others, etc…) tend to make $N_e$ lower than census size (N).

**$F_{IS}$** – Correlation of alleles in an individual relative to the subpopulation in which it occurs. Commonly used as a measure of departure from random mating within a subpopulation.

**$F_{ST}$** – Correlation of alleles within the same subpopulation relative to the entire population. Commonly used as a measure of divergence between subpopulations.

**Gene flow** – Movement of genetic material from one population to another. Implies both physical movement and successful integration into the recipient population.

**Genetic Drift** – Process of genetic divergence between populations based on random sampling of alleles each generation.

**Heterozygosity** – Proportion of individuals in a population that are heterozygotes (i.e. do not have two identical alleles at a locus).

**Hardy-Weinberg Equilibrium (HWE)** – Genotype ratios expected under a random mating model.

**Linkage Disequilibrium (LD)** – A measure of departure from independence of alleles in a pair of loci.

**Locus** – A physical location on the DNA of an organism. The term “locus” is often used synonymously with “marker” or with any type of marker (e.g., “SNP” or “microsatellite”).