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ABSTRACT: We evaluated scale pattern analysis, specifically linear discriminant function analysis and bivariate normal-density contour plots, as a tool to identify sockeye salmon *Oncorhynchus nerka* stocks returning to Upper Cook Inlet. Overall mean classification accuracy for 3-way, Kenai-Kasilof-Susitna River discriminant models ranged from 62 to 75% for the years 1983–1988. Bivariate normal-density contour plots of scale variables revealed a lack of consistency in size and shape and had significant overlap among stocks. Significant temporal and sexual intrasystem differences in scale variables were detected. Scale pattern has not provided the precision needed to effectively manage salmon stocks returning to Upper Cook Inlet.

INTRODUCTION

Management of sockeye salmon *Oncorhynchus nerka* stocks throughout Alaska are predicated on attaining fixed, system-specific escapement goals, which presumably maximize the long-term sustainable yield. To harvest surplus production beyond targeted escapements, the fishery manager needs reliable estimates or indices of stock contributions to area-specific commercial harvests, usually within 24–72 h after a commercial harvest has occurred. Thus, in 1976 the Alaska Department of Fish and Game (ADF&G) initiated sockeye salmon stock identification research in Upper Cook Inlet (UCI; Figure 1), Alaska, to provide estimates of stock composition in commercial fishery harvests.

UCI is presently divided into 2 commercial fishery management districts: the Central District, composed of 6 subdistricts, and the Northern District composed of 2 subdistricts. With the exception of Chinitna Bay in the Central District, where purse seines are used, gillnets are the only legal salmon fishing gear in UCI. Set and drift gillnets are allowed by regulation in the Central District, but only set gillnetting is permitted in the Northern District. Approximately 600 drift gillnet permit holders fish the Central District, and between 550 and 600 set gillnet permit holders fish annually throughout UCI. The fishing season generally extends from the end of June until mid August.

Major portions of UCI sockeye salmon spawning and rearing areas are found in the Kenai, Kasilof, Crescent, and Susitna drainages (Figure 1). The single largest producer of sockeye salmon is the Kenai River drainage, average annual runs approaching 3.0 million fish. Cook Inlet's second and third largest producers of sockeye salmon are the Kasilof River and Susitna River drainages. These systems combined produce runs averaging 1.0–1.5 million fish. The fourth largest producer of sockeye salmon is the Crescent River drainage with an average run of 200 thousand fish. Beyond the stocks of the major drainages, there are many so-called minor stocks that lack routine, annual run-strength assessment.

Two approaches were initially investigated for stock separation in UCI, one using genetically inherited proteins and mixture-model analysis (Grant et al. 1980) and the other using scales and linear discriminant function (LDF) analysis or scale pattern analysis (SPA; Krasnowski and Bethe 1978). SPA was subsequently used because it was a proven technique for deciding racial origins of salmon captured on the high seas and along the Pacific coast region. Also, results could be obtained within 24–72 h following a commercial fishery (Henry 1961; Mosher 1963; Anas 1964;

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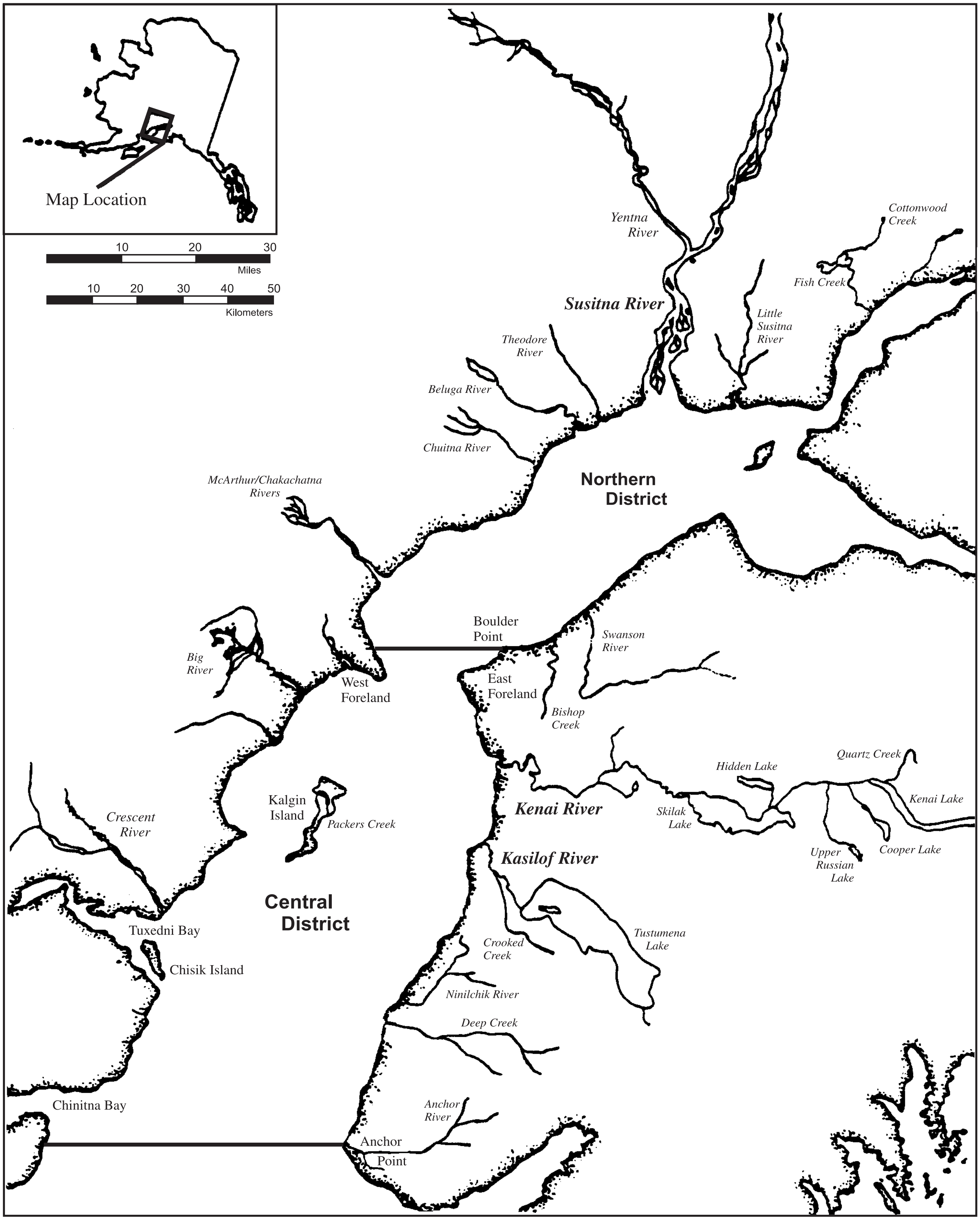


Figure 1. Upper Cook Inlet showing locations of the Northern and Central Districts and the primary salmon spawning drainages.

Wright 1965; Anas and Murai 1969; Lechner 1969; Major et al. 1973; Conrad 1984; Marshall et al. 1987). Therefore, between 1977 and 1986 SPA methodology was an integral part of the UCI salmon management and research programs.

By 1987 fishery managers noticed that the estimates of harvest contribution did not agree with other indicators of run strength, such as escapement estimates (P. Ruesch, Alaska Department of Fish and Game, Soldotna, personal communication). At critical management times during the season, contribution estimates for the Susitna River in the Central District drift gillnet harvests using SPA were typically 30% or less with 90% confidence intervals of ±20% or greater (Bethe and Krasnowski 1979; Bethe et al. 1980; Cross et al. 1981, 1982, 1983, 1985, 1986, 1987; Cross and Goshert 1988; Waltemyer and Tarbox 1988). This level of uncertainty often indicated that the Susitna River run size was either exceptionally weak or very strong; thus, no new information on the Susitna run strength was provided to the manager.

Reasons for low precision in the UCI stock contribution estimates had not been addressed. Consequently, we examined the assumptions of the LDF analysis as they are applied to building scale pattern models. We also evaluated the usefulness of the methodology for assessing UCI sockeye salmon stock contributions.

METHODS

Collection of scale data and the methods used to develop LDF models has remained relatively unchanged since 1979 (Conrad 1985). Scale data were collected from scale images projected onto a digitizing pad and then reformatted to obtain scale variables for use in the analysis (Appendix A). Selection of scale variables for use in the LDF models began by examining for differences between stocks for each scale variable using a 1-way analysis of variance (ANOVA). Scale variables that exhibited a difference were inserted into a stepwise variable selection procedure (Enslein et al. 1977). The stepwise procedure used forward and backward selection with the entry/removal criterion set by the user. Equality of the variance-covariance matrix for the selected variables among stocks was examined using Box's (1949) procedure. The selected scale variables were then used to build an LDF model (Fisher 1936; Morrison 1990).

Prior to 1981, accuracy of the LDF model was evaluated by dividing the scale samples for the known populations into 2 groups: a training sample to build an LDF model and a validation sample to evaluate its performance. From 1981 to present, LDF models were evaluated using a leave-one-out procedure (Lachenbruch 1967). In either case, model accuracy was summarized as a classification matrix, giving each stock the proportions correctly classified and misclassified to other stocks. The overall classification accuracy was estimated as the mean proportion correctly classified.

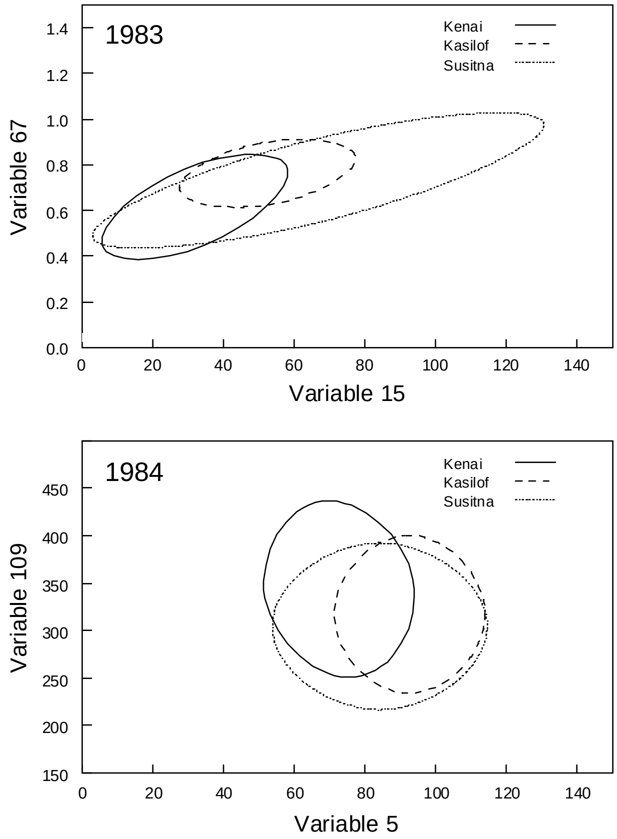


Figure 2. Relationship of the 90% density contours for the first 2 variables in the yearly models for age-1.3 sockeye salmon returning to the Kenai, Kasilof, and Susitna Rivers, Upper Cook Inlet, Alaska, 1983–1984. The Susitna River comprises a weighted sample from the Yentna and mainstem Susitna Rivers.

Samples obtained from UCI sockeye fisheries were classified using the LDF model. The estimates of the proportions of each stock present were adjusted using the Cook and Lord (1978) procedure, and the variance of each adjusted stock contribution estimate was calculated using the methods described by Pella and Robertson (1979).

A thorough review of scale pattern studies in UCI for the years 1977 to 1986 was undertaken using information presented by Bethe and Krasnowski (1979), Bethe et al. (1980), Cross et al. (1981, 1982, 1983,

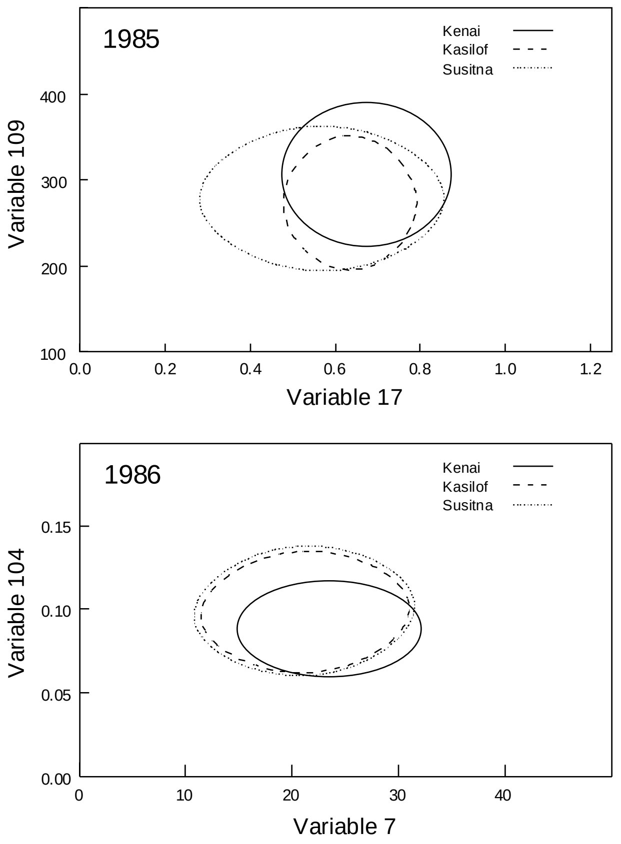
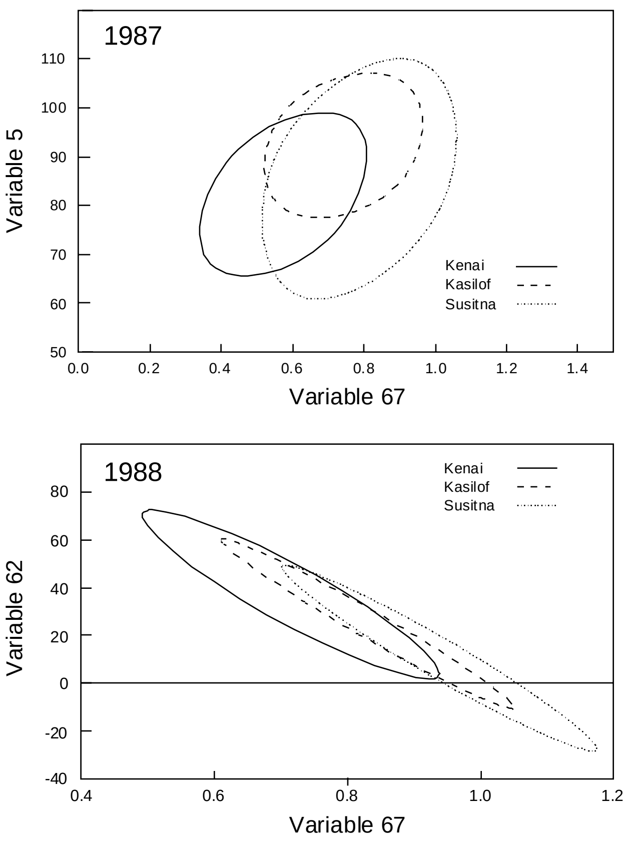


Figure 3. Relationship of the 90% density contours for the first 2 variables in the yearly models for age-1.3 sockeye salmon returning to the Kenai, Kasilof, and Susitna Rivers in Upper Cook Inlet, Alaska, 1985–1986. The Susitna River comprises a weighted sample from the Yentna and mainstem Susitna Rivers.



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1985, 1986, 1987), Cross and Goshert (1988), and Waltemyer and Tarbox (1988). Concerns focused on age-1.3 sockeye salmon, typically the dominant age class in the UCI commercial sockeye salmon harvests. Three-stock LDF models (the employed model) constructed by the original analysts were chosen for our investigation; these were the Kenai, Kasilof, and Susitna stocks (Figure 1). We examined numbers of variables in these annual models, variables used, and their mean classification accuracies. Stocks of 1983 through 1988 were visually distinguished using plots of bivariate normal-density contours. The 90% bivariate normal-density contour was estimated (Meyer 1975) for each stock for the first 2 scale variables resulting from the stepwise-selection procedure. The first 2 variables generally account for most of the discriminating ability as measured by the mean classification accuracy (45% to 69%; Cross et al. 1986, 1987; Cross and Goshert 1988; Waltemyer and Tarbox 1988, 1991).

SPA for estimating inseason stock contributions to UCI commercial harvests required an assumption of stability in scale characteristics through time. Inseason harvest contribution estimates were made using an LDF model constructed from scales collected from the early portion of the escapement prior to the fishery. Although fish subsequently harvested in the commercial fishery were from the same 3 stocks, their later timing may not have been well represented by the LDF model.

For the years 1988–1990, we tested model scale variables for temporal differences. All usable age-1.3 scales collected from the Kenai, Kasilof, and Yentna (a tributary to the Susitna River) River escapements for the years 1988 through 1990 were digitized. The yearly scale data were stratified into 2 or 3 time intervals and analyzed for differences both through time and between sexes. The time intervals were obtained by adjusting cutoff dates to obtain sample sizes ranging from 60 to 200 observations in each period. A 2-way

Table 1. Numbers and identity of variables selected by the stepwise selection procedure for use in the 3-way (Kenai-Kasilof-Susitna) age-1.3 linear discriminant models, 1983–1988. Variables are defined in Appendix A.

		Freshwater Variables																Marine Variables										
Year	Number of Variables	2	5	7	12	14	15	16	17	18	25	26	28	61	62	66	67	70	72	80	89	93	94	104	105	106	108	109
1983	10	x	x				x		x	x	x						x					x					x	x
1984	11		x				x		x		x	x	x				x	x					x			x		x
1985	11	x					x	x	x		x			x		x							x	x		x		x
1986	10	x		x				x						x		x		x	x					x	x			x
1987	7		x								x				x		x			x	x							x
1988	9				x	x							x	x	x		x				x				x			x
Frequency		3	3	1	1	1	3	2	3	1	4	1	2	3	2	2	4	2	1	1	2	1	2	2	2	2	1	6

Table 2. Order of variable input and mean classification accuracy (in parentheses) for age-1.3 Kenai-Kasilof-Susitna River linear discriminant models, 1983–1988. Variables are defined in Appendix A.

	Variable Number (Mean Classification Accuracy)											
	Order of Variable Input into Annual Model											
Year	1	2	3	4	5	6	7	8	9	10	11	Box's Test[a]
1983	15(0.65)	67(0.69)	109(0.70)	93(0.71)	25(0.70)	17(0.70)	5(0.71)	108(0.72)	2(0.72)	18(0.73)		<0.001
1984	5(0.61)	109(0.64)	70(0.68)	67(0.68)	25(0.68)	94(0.69)	28(0.68)	17(0.70)	26(0.70)	106(0.70)	15(0.71)	<0.001
1985	17(0.50)	109(0.55)	94(0.57)	25(0.58)	16(0.59)	15(0.60)	2(0.60)	104(0.59)	61(0.61)	66(0.65)	106(0.66)	<0.001
1986	7(0.44)	104(0.45)	66(0.51)	61(0.54)	2(0.57)	105(0.60)	109(0.61)	72(0.61)	16(0.60)	70(0.62)		<0.001
1987	67(0.61)	25(0.69)	5(0.70)	109(0.72)	89(0.73)	62(0.73)	80(0.73)					<0.001
1988	67(0.64)	62(0.67)	109(0.68)	28(0.73)	12(0.73)	89(0.74)	14(0.74)	105(0.75)	61(0.75)			<0.001

[a] Probability of equal variance-covariance among groups (Box 1949).

Table 3. Summary of test results for the evaluation of temporal changes in scale variables for the Kenai, Kasilof, and Yentna (Susitna) Rivers, age-1.3 sockeye salmon, 1988–1990. Statistically significant test results ($\alpha = 0.05$) are indicated with an asterisk (*).

River	Year	Number of Time Strata	Sample Size Time Strata	Test	Probability of a Greater F		
					Time	Sex	Interaction
Kenai River:							
	1988	3	t_1=182	MANOVA	<0.001 *	0.006 *	0.163
			t_2=163				
			t_3=133	ANOVA			
				Variable			
				67	<0.001 *	0.206	0.116
				109	<0.001 *	0.417	0.509
				70	0.047 *	0.065	0.057
				26	<0.001 *	0.225	0.042 *
				14	0.011 *	0.800	0.695
				16	<0.001 *	0.329	0.769
				1	<0.001 *	0.539	0.499
				4	<0.001 *	0.083	0.318
	1989	3	t_1=158	MANOVA	<0.001 *	0.252	0.867
			t_2=138				
			t_3=100	ANOVA			
				Variable			
				2	<0.001 *	0.711	0.975
				1	<0.001 *	0.961	0.872
				109	<0.001 *	0.038 *	0.902
				67	<0.001 *	0.503	0.577
	1990	2	t_1=72	MANOVA	0.831	0.732	0.767
			t_2=60				
Kasilof River:							
	1988	3	t_1=194	MANOVA	<0.001 *	0.039 *	0.440
			t_3=201	ANOVA			
				Variable			
				67	0.177	0.359	0.614
				109	<0.001 *	0.904	0.561
				70	0.681	0.884	0.244
				26	0.625	0.002 *	0.205
				14	<0.001 *	0.574	0.769
				16	<0.001 *	0.493	0.574
				1	0.004 *	0.158	0.988
				4	0.079	0.165	0.485
	1989	2	t_1=80	MANOVA	0.462	0.750	0.821
			t_2=63				

- *continued* -

Table 3. (continued)

					Probability of a Greater *F*		
River	Year	Number of Time Strata	Sample Size Time Strata	Test	Time	Sex	Interaction
Yentna River:							
	1988	2	t_1=195 t_2=180	MANOVA	0.336	0.001 *	0.745
				ANOVA Variable			
				67	0.054	0.717	0.643
				109	0.457	<0.001 *	0.768
				70	0.342	0.902	0.765
				26	0.236	0.860	0.998
				14	0.320	0.206	0.864
				16	0.298	0.264	0.595
				1	0.240	0.192	0.796
				4	0.794	0.835	0.642
	1989	2	t_1=94 t_2=121	MANOVA	0.443	0.011 *	0.323
				ANOVA Variable			
				2	0.057	0.015 *	0.997
				1	0.038 *	0.024 *	0.414
				109	0.817	0.022 *	0.671
				67	0.135	0.178	0.537
	1990	2	t_1=91 t_2=85	MANOVA	0.530	0.072	0.315

multivariate analysis of variance (MANOVA) was used to test for differences among rivers and time intervals and between sexes for each variable used in the employed LDF model for each year. If a difference was detected by the MANOVA, a 1-way ANOVA was applied to obtain additional information as to which scale variables differed through time or between sexes. All tests were performed using the SAS GLM procedure (SAS Institute, Inc. 1987) at $\alpha = 0.05$.

RESULTS

The scale variables considered for incorporation into LDF models and the selection procedures used have changed over the years, with some standardization since 1983 (Cross et al. 1986). In 1977, 8 scale variables were considered for an age-1.3 scale model. As the project evolved, the number of scale variables considered for use in the models increased to 18 in 1978 and 75 in 1983. In 1980 the second and third marine zones were excluded from the analysis (Cross et al. 1982). In 1982, variables that were significantly different between sexes were excluded, as were all variables that were not normally distributed (Cross et al. 1985). However, since 1983 (except for 1985) all variables through the second marine zone were included in the stepwise-selection procedure irrespective of sex or distribution characteristics. The entry/removal criterion (*F*-statistic) for the stepwise-selection procedure was set at 1.0 for 1979–1980 and at 4.0 for 1981–1986.

In the 3-way, age-1.3 LDF models, 7 (1987) to 11 (1984 and 1985) variables were used (Table 1). Size of second marine zone (variable 109; Appendix A) was selected and entered into the employed yearly models with the greatest frequency. The next most frequently entered variables were relative distances in the first freshwater zone (variable 25) and the freshwater and "plus" growth zones combined (variable 67). The mean classification accuracy for the LDF models developed from 1983 through 1988 ranged from 62 to 75% (Table 2). The first 2 variables selected in the model accounted for the greatest gain in mean classification accuracy, ranging from 45% in 1986 to 69% in 1983. Box's test for equality of variance-covariance matrices indicated significant differences among stocks for all years examined (Table 2).

Bivariate normal-density contour plots of the first 2 variables in the yearly models showed considerable overlap (Figures 2–4). A lack of visual separation between stocks supports the low mean classification accuracy (Table 2). Susitna River density contours were noticeably larger in 1983–1985 and in 1987 than the Kenai or Kasilof River contours, indicating higher within-river variability in scale variables. Also, the size and shape of the density contours among the 3 river systems within years were not the same, thereby supporting results of Box's test for variance-covariance structure of the scale data.

The Kenai River had significant time ($P > 0.001$) and sex ($P = 0.006$) effects in the array of scale variables in 1988, a significant time effect in 1989 ($P > 0.001$), and no detected time or sex effects in 1990 ($P > 0.730$ for all tests; Table 3). No significant time-sex interactions were detected ($P > 0.160$ for all years). Further evaluation of individual scale variables indicated significant time effects for each of the scale variables included in the LDF models in 1988 and 1989 (Table 3).

The Kasilof River had significant time ($P > 0.001$) and sex ($P = 0.039$) effects in the array of scale variables in 1988, and no detected time or sex effects in 1989 ($P > 0.460$ for all tests; Table 3). No significant time-sex interactions were detected ($P > 0.440$ for both years). Further examination of 1988 individual scale variables indicated that 4 of the 8 scale variables included in the LDF model had significant time effects, whereas only 1 of the 8 variables had a significant sex effect (Table 3).

The Yentna River had no statistically significant time effects ($P > 0.336$) but had significant sex effects ($P < 0.020$) in the array of scale variables in 1988 and 1989; no effects were observed in 1990 ($P > 0.070$ for all tests). No significant time-sex interactions were detected ($P > 0.310$ for all years). Further examination of individual scale variables indicated that 1 scale variable out of 8 examined in 1988 and 3 out of 4 examined in 1989 differed significantly between the sexes (Table 3).

Table 4. Range of mean classification accuracies for Alaskan sockeye salmon stock identification studies in Upper Cook Inlet, Southeast Alaska, and Bristol Bay. All studies used 3-way linear discriminant models.

Location	Age Group	Range of Mean Classification Accuracies (Year)
Upper Cook Inlet[a]	age 1.3	low 0.55 (1980) high 0.75 (1988)
Southeast Alaska[b]	age 1.3	low 0.76 high 0.83
Bristol Bay[c]	age 1.3	low 0.54 high 0.66
Bristol Bay[d]	age 1.3	low 0.67 (1986) high 0.85 (1988)
	age 2.2	low 0.70 (1994) high 0.89 (1992)

[a] Bethe and Krasnowski (1979); Bethe et al. (1980); Cross et al. (1981, 1982, 1983, 1985, 1986, 1987); Cross and Goshert (1988); Waltemyer and Tarbox (1988, 1991).
[b] G. Oliver ADF&G (Anchorage, personal communications).
[c] Van Alen (1982).
[d] Bue et al. (1986); Cross and Stratton (1991); Stratton et al. (1992, 1994); Cross et al. (1992).

DISCUSSION

The goal of SPA in UCI was to provide managers with useful assessments of the composition of mixed stock harvests. In general, the 3-stock models had mean classification accuracies ranging from 55 to 75% that were similar to those found in other SPA studies (Table 4). This led UCI staff to use the technique for inseason management between 1977 and 1986. However, at times knowledge of the fisheries, combined with other biological data, indicated serious errors in the interpretation of SPA results. As a result, UCI staff accepted the SPA estimates only when they were consistent with other knowledge and experience and rejected SPA results that were not consistent.

Separation for the 1983–1988 models was minimal as evidenced by the mean classification accuracies, bivariate contour plots, and relatively large number of variables used in the models (Table 2). The assumption of a common variance-covariance matrix was violated in the 1983–1988 models as evidenced by Box's test and the unequal size and shape of the bivariate contour plots. Investigations using LDF techniques assume that arrays of scale variables are multivariate normal with a common variance-covariance matrix among stocks (Cochran 1964; Horton et al. 1968; Glick 1973). Violations of these assumptions may not affect model performance in cases where the differences between stocks are sufficient to provide clear separation, but they may induce bias as separation is reduced that relates to the probability, or risk, that a fish belongs to a particular stock.

Differences in scale variables among time strata and between sexes, together with poor model performance, indicate that SPA is inappropriate for inseason estimates of stock composition in UCI commercial harvests. Erroneous estimates can confuse managers who have information from other sources that may be more accurate. Sometimes poor fishery management decisions can result, depending on the credibility given the various information sources. Specifically, optimal harvest strategies become ineffective.

Based on our review, (1) the difference in measured scale variables among stocks was minimal, (2) the assumption of common variance-covariance matrix was consistently violated, and (3) scale variables change as the season progresses and differ between sexes. Such biases have exposed these minor stocks to overharvest (P. Ruesch, ADF&G, Soldotna, personal communication). Therefore, we recommend against the use of SPA to assign commercial harvests of UCI sockeye salmon stocks to river of origin. Other biological discriminators, including parasites (Tarbox et al. 1991; Waltemyer et al. 1993) and genetic characters (Tarbox 1993), must be explored and evaluated. Hopefully, some combination of scales, parasites, and genetic characters will provide the basis for a reliable, inseason stock identification program for UCI sockeye salmon stocks.

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Appendix A. Scale variables examined for use in the development of linear discriminators for age-1.2, -1.3 and -2.3 sockeye salmon, Upper Cook Inlet, Alaska, 1983–1988.

Variable Number	Variable Description
	First Freshwater Annular Zone
1	Number of circuli first freshwater (NC1FW)
2	Size (width) of first freshwater (S1FW)
3 (16)	Distance, scale focus (C0) to circulus 2 (C2)
4 (17)	Distance, C0-C4
5 (18)	Distance, C0-C6
6 (19)	Distance, C0-C8
7 (20)	Distance, C2-C4
8 (21)	Distance, C2-C6
9 (22)	Distance, C2-C8
10 (23)	Distance, C4-C6
11 (24)	Distance, C4-C8
12 (25)	Distance, C(NC-4) to end of zone
13 (26)	Distance, C(NC-2) to end of zone
14	Distance, C2 to end of zone
15	Distance, C4 to end of zone
16 thru 26	Relative widths, (variables 3-13)/S1FW
27	Average interval between circuli, S1FW/NC1FW
28	Number of circuli in first 3/4 of zone,
29	Maximum distance between 2 consecutive circuli
30	Relative width, (variable 29)/S1FW
	Second Freshwater Annular Zone
31	Number of circuli, NC2FW
32	Width of zone, S2FW
33 (46)	Distance, end of first annular zone (E1FW) to C2
34 (47)	Distance, E1FW-C4
35 (48)	Distance, E1FW-C6
36 (49)	Distance, E1FW-C8
37 (50)	Distance, C2-C4
38 (51)	Distance, C2-C6
39 (52)	Distance, C2-C8
40 (53)	Distance, C4-C6
41 (54)	Distance, C4-C8
42 (55)	Distance, C(NC2FW-4) to end of zone
43 (56)	Distance, C(NC2FW-2) to end of zone
44	Distance, C2 to end of zone
45	Distance, C4 to end of zone
46 thru 56	Relative widths, (variables 33-43)/S2FW
57	Average interval width between circuli, S2FW/NC2FW
58	Number of circuli in first 3/4 of zone
59	Maximum distance between 2 consecutive circuli
60	Relative width, (variable 59)/S2FW
	Plus Growth Zone
61	Number of circuli (NCPG)
62	Width of zone (SPGZ)
	Freshwater and Plus Growth Zones
63	Total number of annular circuli (NC1 + NC2)
64	Total width of annular zone (S1FW + S2FW)
65	Total number of freshwater circuli (variable 63 + NCPG)
66	Total width of freshwater zone (variable 64 + SPGZ)
67	Relative width, (variable 2)/(variable 66)
68	Relative width, (variable 62)/(variable 66)
69	Relative width, (variable 32)/(variable 66)

- continued -

Appendix A. (continued)

Variable Number	Variable Description
	First Marine Annular Zone
70	Number of circuli (NC1OZ)
71	Width of zone (S1OZ)
72 (90)	Distance, end of freshwater growth (EFW) to C3
73 (91)	Distance, EFW-C6
74 (92)	Distance, EFW-C9
75 (93)	Distance, EFW-C12
76 (94)	Distance, EFW-C15
77 (95)	Distance, C3-C6
78 (96)	Distance, C3-C9
79 (97)	Distance, C3-C12
80 (98)	Distance, C3-C15
81 (99)	Distance, C6-C9
82 (100)	Distance, C6-C12
83 (101)	Distance, C6-C15
84 (102)	Distance, C9-C15
85 (103)	Distance, C(NC10Z-6) to end of zone
86 (104)	Distance, C(NC1OZ-3) to end of zone
87	Distance, C3 to end of zone
88	Distance, C9 to end of zone
89	Distance, C15 to end of zone
90 thru 104	Relative widths, (variables 72-86)/S1OZ
105	Average interval between circuli, S1OZ/NC1OZ
106	Number of circuli in first 1/2 of zone
107	Maximum distance between 2 consecutive circuli
108	Relative width, (variable 107)/S1OZ
	Second Marine Annular Zone
109	Width of second ocean zone