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HERRING SPAWN DEPOSITION AND REPRODUCTIVE IMPAIRMENT

by

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Exxon Valdez Oil Spill
Restoration Project Annual Report

Herring Spawn Deposition and Reproductive Impairment
Restoration Project 95166
Annual Report

This annual report has been prepared for peer review as part of the *Exxon Valdez* Oil Spill Trustee Council restoration program for the purpose of assessing project progress. Peer review comments have not been addressed in this annual report.

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Herring Spawn Deposition and Reproductive Imipairment

Restoration Project 95166
Annual Report

Study History: This project was initiated in 1989 as Natural Resources Damage Assessment Fish/Shellfish Study Number 11 under the title Injury to Prince William Sound Herring. Annual reports were issued in 1990 and 1991 and a number of contractor reports were submitted detailing individual research components. Project funding was continued in 1992, but was discontinued in 1993 and the project went into close out. A final report for research conducted from 1989 through 1992 was submitted in December 1994 (Brown, E.D. 1995. Injury to Prince William Sound herring following the *Exxon Valdez* oil spill). This final report was comprised of 8 chapters representing accepted or submitted journal articles covering most of the research topics investigated by this project. Due to an unanticipated decline in the abundance of spawning adults during 1993, stock assessment and genetic damage studies were reinitiated as Project 94166. This report covers the stock assessment component for spawn deposition biomass estimates and egg loss studies. This project will be continued in FY96 as project 96166 with refinements to improve the accuracy and efficiency of herring biomass estimates.

Abstract: Underwater dive surveys of deposited eggs and acoustic techniques were used to estimate the 1995 adult spawning population of Pacific herring *Clupea pallasi* in Prince William Sound. A stratified random sampling design was employed to estimate the number of herring eggs deposited. Divers estimated the number of eggs within a systematically placed 0.1^2 m quadrat along transects randomly selected from all areas of spawn identified during aerial surveys. Diver estimates of egg numbers were corrected for systematic bias using an inverse prediction procedure that compared diver egg counts and gravimetrically determined laboratory egg counts for the same quadrats. The spawn deposition estimate of the spawning biomass of herring was 18,163.4 tonnes with a 95% confidence interval ranging from 11,410.4 tonnes to 24,916.4 tonnes. The biomass of herring migrating to Prince William Sound spawning grounds was also estimated acoustically in the spring of 1995 using echointegration techniques. Net sampling was conducted to estimate species, size and age composition of the insonified fish. The biomass estimate from the spring of 1995 acoustic survey was 12,000 tonnes. The acoustic biomass estimates are being compared with spawn deposition biomass estimates to evaluate the cost effectiveness and accuracy of each method. These estimates of spawning biomass are used in conjunction with aerial observations of spawn distribution and basic biological information (age composition, sex ratios, average size and fecundity) to forecast spawning returns the following year using an age structured assessment population model. The second component of this project relates to the factors affecting egg loss of PWS herring. The proportion of eggs lost through physical removal and the mortality rate of remaining eggs was investigated to improve diver survey biomass

estimates and our understanding of the mechanisms controlling early life history survival. Prior to 1994, a 10% egg loss was assumed for surveys conducted 5-6 days after spawning based on values recommended in the literature. Results indicate that egg loss rates are highly variable, site specific and are generally higher than previously estimated. Depth and wave exposure accounted for much of the variation in instantaneous egg loss rates in the Montague Island area.

Key Words: *Exxon Valdez* Oil Spill, herring, *Clupea pallasi*, spawn deposition surveys, spawning biomass, Prince William Sound, stock assessment.

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INTRODUCTION

This project estimated the biomass of spawning adult Pacific herring *Clupea pallasi* in Prince William Sound (PWS) using underwater diver surveys of deposited eggs and hydroacoustic techniques. This measure of abundance is necessary for monitoring recovery of the injured herring population, including recovery to population levels sufficient for sustainable commercial harvest. In addition, this project collected information about natural losses of deposited eggs which will be used to improve spawner biomass estimates and to provide early life history abundance and survival information to improve understanding of the ecological importance of herring in the PWS ecosystem. Herring provide important forage for many species including some species severely injured by the *Exxon Valdez* oil spill. Predator species include humpbacked whales, seals, sea lions, gulls, sea ducks, shorebirds, halibut, salmon, rockfish, and other fish. In addition to their ecological value, herring are a major commercial resource in PWS. From 1969 to 1993, the average annual combined ex-vessel value of five commercial PWS herring fisheries was $8.3 million. In addition, several thousand pounds of herring and herring spawn on kelp are harvested annually for subsistence purposes and form an important part of the local native culture of Chenega and Tatitlek.

Relation to Other Oil Spill Studies

The *Exxon Valdez* oil spill coincided with the spring migration of herring to spawning grounds and adult herring swam through oiled waters on their way to nearshore staging areas. Studies of oil spill injuries to herring were initiated in 1989 and research continued through 1992 with contributions from both state general funds and the Trustee Council (Brown 1995). Significant histopathological damage was measured in adults collected in oiled areas in both 1989 and 1990 confirming exposure of the fish to toxins. Oiling of spawning areas caused elevated levels of physical and genetic abnormalities in newly hatched larvae and reduced hatching success of the embryos. Additionally, most of the PWS herring summer rearing and feeding areas were oiled in 1989, based on the oil trajectory and historic fisheries records since 1914 (Reid 1971).

Mortality of young herring was significantly greater in oiled areas in 1989 and 1990, and sublethal effects were measurable in larvae and adults in 1989 and 1990 (Brown 1995). Persistent sheening and suspended oil-sediment droplets leaching from beaches and cleaning operations in 1989 and 1990 continued to expose adult and juvenile herring to oil. Laboratory exposures of pre-spawning adult herring to oil showed high concentrations of oil in ovarian tissue (Brown 1995). Laboratory studies measuring the effect of known doses of oil on newly hatched larvae linked estimated doses of oil measured in PWS and injuries observed in field samples. In addition, measurements of oil in tissues from mussels collected at PWS beaches were significantly correlated to indices of injury in herring larvae from

spawning beds adjacent to mussel collection sites, and were most correlated with genetic injury endpoints (Brown 1995).

Although herring survival varies tremendously under normal conditions, abundance for the 1989 year class is extremely low and results to date strongly implicate the spill as a major cause. One hypothesis is that injury to germ tissue caused by exposure to oil would result in non-viable embryos and larvae. A pilot experiment to measure the ability of herring from this age class to produce viable offspring was conducted in 1992 and hatching success of eggs collected from fish spawning in previously oiled areas was less than half that of eggs collected from fish spawning in pristine areas. Additionally, there were approximately twice as many abnormal larvae from fish spawning in previously oiled areas. Information from this pilot study was used to formulate a study design for the reproductive impairment component of project 94166, which will be reported under a separate cover by NOAA Auke Bay Lab.

In 1993, the total observed spawning population was less than one third of preseason predictions and the average sizes of herring in each age class were some of the smallest on record. The total commercial harvest for that year was one of the lowest on record. Pathology studies from the spring of 1993 implicated viral hemorrhagic septicemia (VHS) as a potential source of mortality and stress (Meyers et al. 1994). Investigations of the incidence and effects of diseases occurring in PWS herring were continued in 1994 and 1995. Spawn deposition surveys were not conducted in 1993, but an acoustic survey was conducted near Green and Montague Islands to obtain an updated estimate of the population size following the apparent high mortality of the previous winter.

OBJECTIVES

1. Estimate the biomass of spawning herring in PWS using SCUBA diving spawn deposition survey techniques such that the estimate is within $\pm$ 25% of the true value 95% of the time.

2. Quantify egg loss rates (the proportion of eggs removed through time) from spawning areas due to wave action, predation, desiccation, or fungal infections between the time of egg deposition (spawning) and the time of hatching. Quantify egg loss by habitat type and egg density.

3. Incorporate egg loss and egg survival estimates with results from previous studies and revise the models as necessary.

4. Define herring spawning habitat types by similarities in temperature, salinity, depth, gradient, substrate, vegetation, and exposure to wave action. Characterize and map habitat utilized for spawning. Estimate the abundance and distribution of adult herring and eggs by habitat type. Test a model of the relationship of spawn timing, spawner density and abundance to egg distribution and density.

5. Incorporate egg loss and survival data with physical oceanographic and meteorological data to formulate and test a model of the relationship of meteorological conditions to wave height and egg desiccation.

6. Test a model of the relationship between predation, wave action, desiccation, fungal infections, habitat type, and egg density.

7. Test a model relating sound-wide embryo survival to habitat type, egg density, and meteorological conditions.

8. Test a model relating historic recruitment success to biological and environmental variables.

METHODS

Spawn Deposition Survey and Biomass Estimation

Biomass estimation based on spawn deposition surveys consisted of three major components: (1) a spawn deposition survey; (2) age-weight-length (AWL), sex ratio, and fecundity sampling; and (3) egg loss determination.

Spawn Deposition Survey Design: Spawn deposition surveys were conducted to obtain biomass estimates within ± 25% of the true biomass 95% of the time. Survey design was described in detail by Biggs and Funk (1988) and followed the two-stage sampling design of similar surveys in British Columbia (Schwiegert et al. 1985) and Southeast Alaska (Blankenbeckler and Larson 1982, 1987). Surveys consisted of random sampling for the first stage (transects) and systematic sampling for the second stage (quadrats within transects). Surveys were stratified by area to account for geographic differences and the potential for discrete herring stocks. Areas surveyed included Southeast, Northeast, and Montague Island (Figure 1).

Mean egg densities along each transect were combined to estimate average egg density by summary area. Spawning bed width along each of the transects was used to estimate average spawning bed width by summary area. Average width, average density, and total spawning bed shoreline length (judged from aerial surveys) were used to estimate total number of eggs deposited in each summary area. Average fecundity and sex ratio obtained from AWL sampling, and estimates of total number of eggs deposited from diver surveys were used to calculate herring population numbers and biomass. Confidence intervals were calculated assuming a normal distribution of total egg estimates.

Spawn Deposition Survey Sampling Procedure:-- The general location of spawning activity was determined from visible milt observed during aerial surveys (Figure 1). Spawning activity was summarized on maps showing spawning locations and the dates on which milt

was observed. Linear distances of shorelines over which herring spawned were estimated directly by aerial surveyors and were later measured from hand drawn aerial survey maps. Hand drawn maps were transcribed to computerized maps and linear distance estimated by the software was compared to surveyor estimates. Aerial observations were corrected using direct observations of eggs at the time of dive surveys.

Mapped shorelines containing herring spawn were divided into the shortest resolvable segments on the map scale (approximately 0.18 km) to aid in locating transects (Figures 2 and 3; Table 1). The total number of potential transects was calculated from the total of all shoreline where spawning was observed. A minimum sampling goal of 0.035 % of all potential transects within the spawning area was set to meet specified accuracy and precision based on variances obtained during 1984, and 1988 to 1992 surveys. Shoreline segments were assigned random numbers and the desired number of transects were randomly selected from among all possible shoreline segments. Each segment selected was assigned a sequential transect number and charted on waterproof field maps. Approximate locations for each transect were obtained from these field maps and exact locations were fixed as the dive skiff approached the shore before bottom profiles, bottom vegetation, or herring spawn became visible from the skiff. Typically, the skiff driver would choose an easily recognizable shoreline feature within the targeted shoreline segment as a reference point (e.g. a tree, rock, or cliff located above the high tide line) to locate the transect. The sampling transect extended seaward along a compass course perpendicular to shore from this fixed reference point.

Diving operations began several days after spawning ceased to allow water turbidity due to milt to decrease and for the large numbers of sea lions usually present near spawning herring to disperse. Two three-person dive teams consisted of a lead diver counting eggs (typically the person most experienced at this survey task), a second diver recording data, and a third diver on the surface serving as a dive tender. Diving and tending duties were rotated daily.

The number of herring eggs occurring within a standardized sampling quadrat was estimated at regular intervals along the length of the transect. The sampling quadrat consisted of a 0.1 m^2 frame constructed of PVC pipe with a depth gauge and compass attached. Location for the first quadrat placement along the transect was haphazardly selected within the first 5 meters of spawn. Succeeding quadrat placements were systematically spaced every 5 meters along the compass course until the apparent end of the spawn. At each quadrat placement, the lead diver estimated the number of eggs in units of thousands (K) within the quadrat and communicated the numbers through hand signals to the second diver. Number of eggs, vegetation type, percent vegetation cover, substrate, and depth were recorded by the second diver in pencil on water-proof plastic paper data forms attached to a clipboard. Divers verified the end of the spawn by swimming at least an additional 20 m past the end of the spawn until a steep drop-off was encountered or vegetation was no longer present.

Biomass Estimation: Analysis of the spawn deposition survey data was similar to methods used in 1988 (Biggs and Funk 1988), and 1989-1992 (Brown 1995). The biomass estimator was

$$B=TB', \tag{1}$$

where

B = estimated spawning biomass in tonnes,
T = estimated total number of eggs (billions) deposited in an area, and
B' = estimated tonnes of spawning biomass required to produce one billion eggs.

Estimates for T and B' were derived from separate sampling programs and were independent. The estimated variance for the product of the independent random variables T and B' was calculated according to Goodman (1960)

$$Var(B)=T^2Var(B')+B^2Var(T)-Var(T)Var(B'), \tag{2}$$

where

Var(B') = an unbiased estimate of the variance of B', and
Var(T) = an unbiased estimate of the variance of T.

Total Number of Eggs (T): The total number of eggs deposited in an area was estimated from a two-stage sampling design using random sampling at the primary stage and systematic sampling at the secondary stage, similar to the design described by Schwiegert et al. (1985). To compute variances based on systematic second stage samples, it was assumed that eggs were randomly distributed in spawning beds with respect to the 0.1 m^2 sampling unit. While this assumption was not examined, in practice the variance component contributed by the second sampling stage is much smaller than that contributed by the first stage and violation of this assumption has little effect on the overall variance. The total number of eggs (T), in billions, in an area was estimated as

$$T=N\hat{y}10^{-6}/(1-R), \tag{3}$$

where

L	=	the shoreline length of the spawn-containing stratum in meters,
N	=	$L/0.1^{0.5}$ = the total number of possible transects,
$0.1^{0.5}$	=	0.3162 m = width of transect strip,
$\hat{y}$	=	average estimated total number of eggs (thousands) per transect,
10^{-6}	=	conversion from thousands to billions of eggs, and
R	=	estimated proportion of eggs disappearing from the study area from the time of spawning to the time of the survey.

Average total number of eggs per transect (in thousands) was estimated as the mean of the total eggs (in thousands) for each transect using

$$\hat{y}=\frac{\sum_{i=1}^{n}\hat{y}_i}{n}, \tag{4}$$

where

$$\hat{y}_i=M_i\bar{y}_i, \tag{5}$$

and

n	=	number of transects actually sampled,
i	=	transect number,
M_i	=	$w_i/0.1^{0.5}$ = number of possible quadrats in transect i,
w_i		spawn patch width in meters measured as the distance along the transect between the first quadrat containing eggs and the last quadrat containing eggs, and
$\bar{y}_i$	=	average quadrat egg count in transect i (in thousands of eggs).

Average quadrat egg count within a transect, $\bar{y}_i$, was computed as

$$\bar{y}_i=\frac{\sum_{j=1}^{m_i}y_{ij}}{m_i}, \tag{6}$$

where

j	=	quadrat number within transect i,
m_i	=	number of quadrats actually sampled in transect i, and

y_{ij} = adjusted diver-estimated egg count (in thousands of eggs) from the diver calibration model for quadrat j in transect i.

The variance of T, ignoring the unknown variability in R, was similar to that given by Cochran (1963) for three stage sampling with primary units of equal size. In this case the expression was modified because the primary units (transects) did not contain equal numbers of secondary units (quadrats), and the variance term for the third stage comes from the regression model used in the diver calibration samples. Therefore the estimated variance of T, conditioned on R, was

$$Var(T) = \frac{[N^2(10^{-6})^2[\frac{(1-f_1)}{n}s_1^2 + \frac{f_1(1-f_2)}{\sum_{i=1}^{n} m_i}s_2^2 + \frac{f_1 f_2}{\sum_{i=1}^{n} m_i}s_3^2]]}{(1-R)^2}, \quad (7)$$

where

$$s_1^2 = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2}{n-1} = \quad (8)$$

variance among transects,

$$s_2^2 = \sum_{i=1}^{n} M_i^2 \sum_{j=1}^{m_i} \frac{(y_{ij} - \bar{y}_i)^2}{n(m_i - 1)} = \quad (9)$$

variance among quadrats,

$$s_3^2 = \sum_{i=1}^{n} \sum_{j=1}^{m_i} Var(y_{ij}) = \quad (10)$$

sum of the variances of the individual predicted quadrat egg counts from the diver calibration model,

$$f_1 = \frac{n}{N} = \tag{11}$$

proportion of possible transects sampled, and

$$f_2 = \frac{m_i}{M_i} = \tag{12}$$

proportion of quadrats sampled within transects (same for all transects).

Diver Calibration Sample Collection: Spawn deposition survey methods for estimating spawning biomass utilize diver estimates of the number of eggs deposited within a systematically placed 0.1 m^2 quadrat. It is possible or even likely that estimates of egg abundance vary considerably from the true abundance. A portion of that variability can be attributed to systematic effects which can be accounted for in a calibration model. Estimates of the effects of vegetation type and diver bias on egg counts were used to adjust the original counts, resulting in more accurate estimates of egg abundance.

Diver calibration samples were collected concurrently with spawn deposition surveys throughout the field season. Calibration samples were stratified by diver, vegetation type within four broad categories, and by egg density over three broad categories. Both divers independently estimated the number of eggs on removable vegetation in each calibration quadrat. All egg-containing vegetation within the quadrat was removed and placed in numbered mesh bags. The number of loose and attached eggs left after removal were estimated by the lead diver and recorded. Based on accuracy estimated for previous survey results, an approximate sample goal of 80 calibration samples was set for each diver with less than three years survey participation and 40 for each calibrated diver who had participated in calibration sampling for three or more years of surveys. Calibration samples for each diver were to be taken equally from each of four vegetation categories: eelgrass (EEL), fucus (FUC), large brown kelp (LBK), and hair kelp (HRK); and equally from each of three ranges of egg densities: low (0-20,000), medium (20,000-80,000), and high (>80,000) within each vegetation category. Aboard the dive vessel, calibration samples were arranged within a sampling quadrat placed on the deck and all divers estimated the number of eggs within the quadrat to increase the number of calibration samples available for each diver and to simulate estimates conducted at low tide. Calibration samples were preserved in Gilson solution and labelled as described by Becker and Biggs (1992). The actual number of eggs present in each calibration sample was later approximated gravimetrically in the laboratory using procedures also described in Becker and Biggs (1992).

Diver Calibration Modelling: Initial analysis of the 1995 spawn deposition diver calibration data was performed by Ed Debevec, ADF&G, Cordova, and is summarized here. More detailed information describing the motivation, methods, and results of his analysis are presented in his original paper as Appendix A.

The diver calibration analyses was done slightly different from that outlined in the 1995 Detailed Project Description. The purpose of the diver calibration is to adjust for systematic biases in the egg count and provide a more accurate estimate. This procedure considered diver and kelp type effects in that different divers may have had very different biases (e.g., one tended to overestimate while another underestimate) and different kelp types may have provided very different conditions for making the estimates. Calibration samples were collected throughout the dive survey and then counted in the lab. Diver calibration was then determined from the relationship between diver counts in the field (dependent variable) and the true lab counts (independent variable), assumed to be without errors. Covariates used in the model were diver and kelp type. Additional factors such as depth of sample, date, and time of day could also be important, but were assumed to be negligible.

Past analyses have used a two-step procedure: (1) pool like groups and (2) obtain calibration parameters for each group. Say we had calibration data for three years for four divers on four different kelp types, for a total of 48 possible groups (3×4×4=48). The process was to determine which groups could be pooled so that we could "beef up" this years' sample sizes. Lab counts are fairly expensive in time and money making it impossible to collect a sufficient set of calibration samples each year. This process was a way to combine all available data to yield more precise adjustments from the resulting larger sample sizes.

It seemed reasonable to combine a diver's calibration data for all years and run a single regression where the observations were weighted by the year it was collected. Specifically, the weights were calculated as

$$weight_i = \frac{1}{96 - year_i} \qquad (13)$$

where $year_i$ is the year that observation i was taken (95, 94, etc.). The result of this is that observations from 1995 received a weight of 1, while those from 1994 had a weight of ½, those from 1992 had a weight of ¼, etc. This was intuitively appealing in that all data from past years were included in the analysis, but the most recent data were considered more important or perhaps more relevant to this year's calibration. Separate regressions were fit for each diver with kelp type used as a class variable in the analysis

Reparameterization was used to obtain directly relevant parameter estimates. For this analysis, each parameter estimate was the slope for a particular year, rather than having some

parameters being the difference in slope between years as would be the case with the usual parameterization. The analyses were run with the intercept forced through zero, egg counts in actual number of eggs (i.e., 100 meant 100 eggs, not 100,000 eggs), and with years pooled. The diver calibration model used was

$$\log(dc_{ijk}) = \beta_{jk}\log(lc_{ijk}) + \epsilon_{ijk} \tag{14}$$

where dc_{ijk} was the ith count for diver j on kelp type k and lc_{ijk} was the associated lab count.

The egg count adjustment used the appropriate parameter estimate (for a given diver and kelp type) in an inverse prediction method of the form

$$adc_{ijk} = e^{\frac{\log(dc_{ijk})}{\hat{\beta}_{jk}}} \tag{15}$$

where adc_{ijk} was the ith adjusted count for diver j on kelp type k. Note that the term adc replaced lc in equation (2) to represent the expected lab count, i.e., the adjusted diver count. Using the delta method, the variance for the adjusted count was determined to be as follows:

$$VAR(adc_{ijk}) = \left(\frac{\log(dc_{ijk})^2 VAR(\hat{\beta}_{jk})}{\hat{\beta}^4_{jk}}\right) e^{\frac{2\log(dc_{ijk})}{\hat{\beta}_{jk}}} \tag{16}$$

Spawning Biomass per Billion Eggs (B'):-- AWL, sex ratio, and fecundity data were used to estimate the relative relationship between spawning biomass and egg deposition. The relationship between fecundity and female weight was used to calculate total number of eggs deposited and tonnes of herring spawners. The tonnes of spawning biomass required to produce one billion eggs (B') was estimated as

$$B' = \frac{\bar{W}S}{F(\bar{W}_f)} 10^3, \tag{17}$$

where

$\bar{W}$ = estimated average weight in grams of all herring (male and female) in the spawning population in an area,

S = estimated ratio of total spawning biomass (male and female) to female spawning biomass,

$F(\bar{W}_f)$ = estimated fecundity at the average weight of females in the spawning population in an area, in numbers of eggs, and

$$10^3 = \text{conversion factor} = \frac{10^{-6}}{10^{-9}} \begin{matrix} \text{grams to tonnes} \\ = \\ \text{eggs to billions} \end{matrix}$$

Because average weight, sex ratio and fecundity were all estimated from the same herring samples, the estimates were not independent. The variance of B' was approximately:

$$\begin{aligned} Var(B') = (10^3)^2 \Big(& \Big[\frac{S}{F(\bar{W}_f)}\Big]^2 Var(\bar{W}) \\ & + \Big[\frac{\bar{W}}{F(\bar{W}_f)}\Big]^2 Var(S) \\ & + \Big[\frac{\bar{W}S}{F(\bar{W}_f)^2}\Big]^2 Var(F(\bar{W}_f)) \\ & + 2Cov(\bar{W},S)\Big[\frac{S}{F(\bar{W}_f)}\Big]\Big[\frac{\bar{W}}{F(\bar{W}_f)}\Big] \\ & - 2Cov[\bar{W},F(\bar{W}_f)]\Big[\frac{S}{F(\bar{W}_f)}\Big]\Big[\frac{\bar{W}S}{F(F(\bar{W}_f))^2}\Big] \\ & - 2Cov[S,F(\bar{W}_f)]\Big[\frac{\bar{W}}{F(\bar{W}_f)}\Big]\Big[\frac{\bar{W}S}{F(\bar{W}_f)^2}\Big]\Big). \end{aligned} \tag{18}$$

Because S was estimated from pooled or single AWL samples (depending on availability of fish), it was not possible to estimate the covariance terms containing S, $Cov(\bar{W},S)$ and $Cov[S,F(\bar{W}_f)]$. Because the term involving $Cov[\bar{W},F(\bar{W}_f)]$ has been shown to be very small

in previous analyses and probably contributes little to Var(B'), these covariance terms were not included in the estimate of Var(B').

Herring Age, Weight, Length, Sex, and Fecundity

Biological samples were collected for age and sex composition, calculation of average weight and length, and estimation of fecundity. Most samples were captured by volunteer commercial seine vessels or vessels under short term contract as part of an existing ADF&G test fishing sampling program. Sampling generally occurred soon after concentrations of herring appeared in nearshore areas becoming accessible to purse seines and continued periodically throughout the spawning migration. Age and sex composition and average herring size were calculated using only AWL samples collected near the peak of spawning as determined from aerial survey sightings of milt and herring schools.

AWL sampling was stratified by date and locality for test fishing catches in spawn deposition summary areas. Sample size for each stratum was set to simultaneously estimate proportions by age when sampling from a multinomial population (Thompson 1987). The goal was to select the smallest sample size for a random sample from a multinomial population such that the probability would be at least $1-\alpha$ (precision = 0.05) that all the estimated proportions were simultaneously within 5% (accuracy = 0.05) of the true population age proportions. A sample size of 450 herring per stratum was selected to ensure that this level of precision and accuracy would be obtained for any number of age classes and proportions when less than 5% of the collected scales were unreadable. Herring AWL sampling procedures are described in greater detail by Baker et al. (1991) and followed standard protocols outlined in project operational manuals (Wilcock *In press*).

Fecundity samples were subsampled from female herring in AWL samples and were stratified by fish length. Egg and gonad weights were measured and used to calculate average fecundity at the average female weight ($F(\bar{W}_f)$). Fecundity sampling goals were set such that fecundity estimates would contribute no more than 1% to the confidence interval width of the biomass estimate. It was determined that a sample size of 150 to 200 herring pooled across areas would be sufficient to maintain the coefficient of variation below 2.0%. To collect females across the range of all possible sizes, sample goals were 20 to 30 females within each 10 mm length category from 181 to 250 mm standard length, and 20 to 30 females 180 mm or smaller. The female gonad weight was the weight of the ovaries removed from each female.

Mean Weight and Sex Ratio: Average weight and sex ratio was estimated as a weighted average of estimates from each sampled locality based on observed aerial survey biomass at each locality. Because biological samples were collected only at Montague Island and because spawning observed in other areas was limited, AWL samples from Montague Island were used to estimate mean weight and sex ratio for all spawn deposition summary areas.

Sex ratio, S, was calculated as the ratio of the number of herring of both sexes in AWL samples to the number of females. The binomial distribution is applicable to estimating the proportion, p, of females in AWL samples, where S = 1/p. The variance of S is

$$Var(S) = \frac{S^2(S-1)}{n}, \tag{19}$$

where n is the number of fish in the AWL sample.

Fecundity for Biomass Estimates: Average fecundity for PWS was estimated from a fecundity-weight relationship as $F(\bar{W}_f)$, and used in equation 17 to estimate biomass from spawn deposition. The variance of estimated average fecundities was approximated by the variance of predicted means from the fecundity-weight linear regression (Draper and Smith 1981)

$$Var[F(\bar{W}_f)] = s^2\left[\frac{1}{n} + \frac{1}{q} + \frac{(\bar{W}_f - \bar{W}\bar{F})^2}{\sum (W_i - \bar{W}\bar{F})^2}\right], \tag{20}$$

where

s^2	=	the residual mean square from the fecundity-weight linear regression,
$\bar{W}_f$	=	the average weight of female fish in the spawning population,
$\bar{W}\bar{F}$	=	the average weight of females in the fecundity sample,
W_i	=	the weights of individual females in the fecundity sample,
n	=	the total number of females in the fecundity sample from each area, and
q	=	the total number of females in the representative AWL sample or pooled samples from the corresponding area.

A linear relationship between female body weight and fecundity was used because Hourston et al. (1981) found that female body weight at spawning explained 70% of the variation in fecundity among individuals, but length and age only explained another 2% of the variation.

Egg Loss Study

The proportion of eggs lost through physical removal and the mortality rate of remaining eggs was investigated to improve diver survey biomass estimates and to improve understanding of the mechanisms controlling early life history survival. The total number of eggs estimated from diver surveys (term T, equation 1) was corrected for eggs lost between the time of

herring spawning and diver surveys as term R in equation 3. In prior spawn deposition studies for PWS, an assumed constant egg loss rate of 10% was used to correct spawn deposition estimates based on values recommended in the literature (Haegele et al. 1981, Blankenbeckler and Larson 1982). This estimated loss was based on the assumption that surveys were generally conducted 5-6 days after spawning. Egg loss was studied during spawn deposition surveys of PWS in 1990 and 1991 to more accurately quantify loss rates (Brown 1995). These studies indicated that egg loss varied substantially over time and between sites and suggested that using a constant rate of 10% may be inappropriate in some instances. These studies also suggested that spawning habitat may play a key role in determining egg loss rates, but the study design did not include collection of data to relate egg loss to habitat type, environmental conditions, or predation. The 1995 study included measurements of 1) slope, substrate, and vegetation to describe habitat characteristics; and 2) temperature and salinity to describe environmental conditions. In addition, information was collected about bird predators in collaboration with EVOS Project 95320Q, Avian Predation on Herring Spawn. A Reimbursable Services Agreement (RSA) was initiated with the University of Alaska to investigate the factors important for estimating egg loss using the results from previous studies and the 1995 study. They also began investigating the modelling of egg loss to eventually construct an embryo survival model. A progress report for this work is included as Appendix B. More detailed descriptions of their analytical methods and results for egg loss studies will be included in their final report, anticipated for late FY96.

Egg Loss Sampling Procedure. Eight transects were established in 1995 on Montague Island to study egg loss (Figure 2; Table 2). Transect locations were chosen to represent typical spawning beach habitat characteristics within the spawn deposition summary area and to cover the range of potential exposures to wave action during incubation. Similar to spawn deposition transects, egg loss transects were established perpendicular to shore following a compass course. Three sampling stations were located along each transect line at depths within the range of usual herring spawn (+1.65 m to -9.90 m). Sampling stations were set at (1) 1.0 m above MLLW, (2) 1.0 m below MLLW, and (3) 3.0 m below MLLW based on information from previous egg loss and egg distribution studies. Station depths for some transects were adjusted according to actual deposition of eggs. Depth at each station was initially determined using SCUBA diver depth gauges and later corrected for tide level. During transect establishment, beach gradient, substrate, and vegetation present at the site were recorded.

A grid of 5 x 2 permanent 0.1 m^2 quadrats was placed along transect lines at each depth station. Grids were generally oriented perpendicular to the transect and parallel to the shoreline, but actual placement was adjusted to conform to bottom contour, occurrence of spawn, and to represent vegetation typical of the site at that depth.

To collect information on egg loss due to predation and wave action, predator exclusion frames were placed at each of the three depth stations along each transect line. Exclusion devices were constructed from steel shrimp trap frames approximately 1 m^3 in volume and

enclosed in mesh. Placement at each depth included: (1) one frame covered with small mesh intended to retain all eggs lost from wave action and to exclude large predators, (2) one frame covered with mesh large enough to exclude avian predators, but which would allow physical egg removal by wave action, and (3) a control plot marked by steel spikes, but without frames or mesh.

Transects were generally visited every three to four days. During each site visit, divers estimated egg density within each of five 0.1 m^2 quadrats along the bottom row of the fixed quadrat grid and the top row was reserved in case of destruction of any quadrats in the bottom row. Divers also collected eggs and vegetation within a separate 0.1 m^2 quadrat haphazardly placed near the egg loss grid for calibration samples. Diver calibration samples were preserved and processed in the same manner as those collected for spawn deposition surveys. During each site visit, measurements were made of air temperature, water temperature, and salinity. In addition, precipitation, tide height, wind speed and direction were noted.

To investigate the range of temperatures to which incubating eggs would be exposed, mechanical temperature recorders were installed at two egg loss sites. However, recorders were not activated properly and only temperatures measured during site visits were collected.

An additional sample containing over 200 eggs, was haphazardly selected from vegetation adjacent to the frames during each visit and depth. For each such sample, live/dead ratios were estimated and the eggs were examined for signs of desiccation or other signs of morbidity. Subsamples of live embryos were also collected just prior to hatch and preserved for later evaluation of morphological abnormalities and cytogenetics. Subsequent funding for processing of these samples was not included in the FY95 work plan.

Near the mid-point date of the incubation period, a sample of potential herring egg predators within an approximately 1 m^2 patch of spawning area adjacent to each egg loss transect was collected for species identification. Eggs and vegetation collected for this sample were preserved in Gilson's solution and all vertebrate and invertebrate animals were frozen. Frozen samples were submitted to nearshore researchers at the University of Alaska Fairbanks for identification.

Acoustic Survey and Biomass Estimation

Standard acoustic techniques (Thorne 1983b; Ehrenberg and Lytle 1972) for echointegration and dual beam processing of target strength were used to independently estimate the biomass of herring present near spawning grounds during the spring migration. Energy reflected from fish concentrations was measured and converted to fish density using measurements of energy reflected from single fish (target strength) and knowledge of the sample volume (transducer directivity). Net sampling was conducted to subsample the acoustic targets to verify species, size and obtain other biological information on the insonified fish.

The acoustic survey employed one commercial purse seiner under short term vessel charter to assist in searching for herring schools and to conduct net sampling. The scientific echosounding equipment was located aboard the ADF&G research vessel *Montague* for acoustic mapping of the biomass. The acoustics vessel was outfitted with a BioSonics 120 Khz echo sounder with a dual beam pre-amplified transducer mounted on a 1.2 m BioSonics Biofin in a down-looking configuration. The Biofin was towed at a depth of about 2 m at approximately 5 m off to one side of the vessel. The catching vessel was equipped with a seine approximately 30 m deep typical of the gear-type used in the commercial sac roe herring fishery.

Survey Design. The acoustic survey followed a multistage sampling design (Cochran 1967). Historical information about location of spawning, aerial surveys of herring schools, and wide scale searches using ship's searchlight (sweeping) and down-looking echosounders was used to locate concentrations of herring schools in a first stage search. The second stage of sampling involved mapping the school groups and measuring the density using the scientific echosounder. Acoustic survey transects were run in a zigzag fashion over the school groups and were replicated during both day and night for large school groups.

Acoustic Parameters Target strength information for herring was derived from average length to target strength (in decibels) per kg fish after Thorne (1983a). Thorne's (1983a) empirical relationship assumes the following logistical equation:

$$\gamma = \frac{\bar{\sigma}}{\bar{W}} = a\bar{l}^{-b} \qquad (21)$$

where σ is the mean acoustic backscattering coefficient, W is the mean weight (in kg), l is the mean length (in cm), and a and b are constants. Values for the constants (a and b) are obtained from data for a variety of fisheries presented by Thorne using a linear regression of $\log_{10}$l versus 10 log (σ/w), where 10 log (σ/w) is referred to in Thorne (1983a) as "target strength per kg." Average herring length and weight data was compiled from samples obtained by the purse seine catcher vessel. These measured data were applied to Thorne's (1983a) empirical relationship to obtain the ratio $\gamma = \sigma$/w and the mean backscatter coefficient (σ). As a cross check, *in situ* measurements of target strength from dual beam acoustic data were generated and compared with Thorne's (1983a) empirical formula.

Biomass Estimation Herring biomass was calculated for each zigzag survey. The general calculation of the population density using echointegration for a single cell *jk* on a transect is given as

$$\beta_{jk}=\rho_{jk}\overline{w}_{jk}=\frac{C(ei)_{jk}\cdot P_{jk}}{\frac{\overline{\sigma}_{jk}}{\overline{w}_{jk}}} \tag{22}$$

where β_{jk} is the population density (mass per unit volume), ρ_{jk} is the density of scatterers, w_{jk} is mean weight of scatterers, C is acoustic constant (calibration settings ie., gain etc.) ei_{jk} is the mean of the voltage squared, P_{jk} is percentage of cell *jk* within the water column, and σ_{jk} is mean backscattering coefficient for targets within cell *jk*.

The biomass for a region of surface area A is determined by using a set of line transects along which a total of nrs point estimates of biomass per unit area is obtained. Specifically,

$$B=\frac{\sum_{j=1}^{nrs}\sum_{k=1}^{nst}\beta_{jk}}{nrs}\cdot A \tag{23}$$

where nrs is number of reports (along the line transects), nst is number of depth strata, and A is survey area.

Herring biomass estimates followed Thorne (1983a), assuming that σ_{jk}/w_{jk} is independent of cell *jk*, hence, for all *jk* σ_{jk}/w_{jk} is a constant γ, and γ is given by equation 21. With this assumption, equation 22 simplifies to:

$$\beta_{jk}=\frac{C}{\gamma}\cdot(ei)_{jk}P_{jk} \tag{24}$$

and the herring biomass B in an area is given as

$$B=\frac{C}{\gamma}\frac{\sum_{j}\sum_{k}\cdot(ei)_{jk}P_{jk}}{nrs}\cdot A \tag{25}$$

RESULTS

Biomass Estimation

The total biomass of herring spawning naturally in PWS during 1995 was estimated to be 18,163 tonnes from spawn deposition diver surveys (Table 3). The variance of this estimated total was high, and the 95% confidence limits ranged from 11,410 tonnes to 24,916 tonnes (Table 4). Most of the estimated biomass spawned in the Montague Island summary area (16,463 tonnes), but small biomasses of spawning herring were calculated for the Southeastern (1390 tonnes) and Northeastern (309 tonnes) summary areas (Figure 1). The total biomass from 1995 was approximately 3,175 tonnes more than the 1994 biomass which was primarily due to more spawn in the northeast and southeast areas of PWS. The total miles of spawn in 1995 increased by approximately 40% from 1994 mainly due to the increases in the northeast and southeast.

Diver Calibration Modelling: The diver calibration method was implemented with adjusted egg counts calculated for the 1995 data. The range of diver calibration counts for 1995 was 0.6 K to 530 K, while it was 0.6 K to 1442 K for all years. The range of diver estimates on sampled quadrats in 1995 was 0 to 2800 K, almost double the maximum calibration point from any year. This raised the concern that we were using the calibration model on points well outside the range of data used to build the model. We could assume the trend continues to these high counts, but that may not be realistic. There appeared to be a tendency for high counts to be more accurate than moderate counts. This can be seen in a plot of all calibration points where the mean diver count is decidely underestimated below around 5.5 on the X-axis, while points greater than 5.5 appear to be centered on the unity line (Figure 4).

Without calibration points to cover the range of the data, it is difficult to model these extreme counts with any kind of certainty. The model over the range of available calibration points resulted in an adjustment that becomes more severe for larger diver estimates. For extremely large estimates, such as 2800 K which is five times the maximum calibration point for 1995, the resulting adjustment would be quite substantial. Based on what little supporting data we have, this does not seem to be realistic.

Several options regarding large diver estimates were considered. The first was to leave the model as it was and run the adjustment. As just stated, this was not considered a realistic option and the resulting five or six extremely large estimates had a substantial effect on the final biomass estimate, varying the result by several thousand tons depending on whether they were included in the analysis or not. The second option was to use the calibration model on diver counts up to some threshold number of eggs, but no adjustment on counts above the threshold. However, this also seemed to be rather extreme. Additionally, there would be an unrealistic discontinuity in the model around the threshold.

A third option was used that was a compromise between the first two. Again, the calibration model was used on diver counts up to a threshold number of eggs. However, instead of

switching to the unity line for points above the threshold, a line parallel to the unity line was used that was continuous with the calibration line. The resulting calibration tended to follow the apparent curve suggested in Figure 4 where estimates seemed to be more accurate at the higher counts. Perhaps non-linear regression could be used to better model the relationship. More essential, though, is the need for more calibration points for higher diver counts.

Herring Age, Weight, Length, Sex, and Fecundity

Age and sex composition and average size at each locality is estimated as part of ongoing ADF&G fishery management activities. These data will be published separately in a regular Commercial Fisheries Management and Development Division reporting series (personal communication, D. Sharp, Alaska Department of Fish and Game, Cordova; unpublished data, J. Wilcock, Alaska Department of Fish and Game, Cordova). The average size at age of all sampled herring and the estimated contribution by age to the 1995 PWS herring biomass is presented in Table 5. As expected from preseason forecasts (Funk 1995), the total biomass consisted largely of age-7 herring from the 1988 year class (52.7% contribution by weight and 44.9% by number). The abundance of herring from the 1989 year class continued to be low and comprised only 2.5% of the total number of fish. Abundance of age 3 fish (24.1% by number) increased over 1994 indicating relatively strong recruiment of the 1992 year class.

The average weight of all sampled herring was 123.0 g and the average length was 211 mm, similar to average weights observed in 1994 (Wilcock et al. 1995). Sex ratios varied between project summary areas, 2.65 for Montague, 2.27 for the Northeast and 2.89 for the Southeast areas. (Table 3). Regression results for the weight to fecundity relationship are presented in Figure 5. Average fecundity of female herring by summary area was similar to fecundity estimated for previous years (Table 3).

Egg Loss Study

Sites for 8 egg loss transects established on Montague Island during 1995 (Figure 2; Table 2) were chosen to represent a range of habitat characteristics over which herring spawn occurred. All sites were visited at least eight times during incubation. Exposures varied from very protected shoreline near the head of Rocky Bay at site 2, to extremely exposed rocky oceanic shoreline at site 6 on Montague Point. Rocky substrates were most frequent (6) at egg loss sites reflecting the selection of this substrate by spawning herring, while sand or mud bottoms occurred at only one site.

Avian predation exclusion frames were installed at all sites, but a number of frames were dislodged by wave action over the course of incubation, particularly the frames enclosed in small mesh. It was also found that algal and detrital build-up was severe on the small mesh frames and that loose eggs tended to drift into the frame from outside the enclosure and accumulate. Because of these shortcomings, small mesh enclosures were not felt to

accurately represent egg loss and were dropped from the analysis. Large mesh frames were less frequently dislodged, and data from these frames will be included in the egg loss completion report. More detailed discussion of avian predator methods and results is included in the annual report for project 95320Q.

Preliminary analysis of egg loss data collected for 1995 was conducted under a reimbursable services agreement with the University of Alaska (Appendix B). They graphically examined 1995 egg loss results as well as results from previous studies to identify factors important for modelling egg loss. More detailed descriptions of their methods and results will be included in the final report for that project component.

Acoustic Survey and Biomass Estimation

The spring 1995 acoustic biomass estimation consisted of five surveys in the Montague Island summary area. Sonar and aerial surveys indicated that this area represented the primary spawning concentration of herring in PWS. Two daytime surveys were conducted in both Rocky Bay and Zaikof Bay, and two night time surveys in Rocky Bay. The average length of herring from samples collected in Rocky Bay was 218 mm, resulting in a scaling factor of -32.3 dB/kg. Average length of herring samples in Zaikof Bay was 184 mm, resulting in a scaling factor of -31.9 dB/kb. The resulting biomass estimates for Rocky Bay was 9,265 tonnes and Zaikof Bay was 2,735 tonnes. Historically, herring acoustic surveys have used -33 dB/kg as the scaling factor regardless of the length of the fish. Using the -33db/kg scaling estimate would have increased the biomass estimate for Rocky Bay by 18% and Zaikof Bay by 29%, respectively. The 1995 spring biomass estimate of 12,000 tonnes for the two areas was similar to the 12,500 tonnes of herring estimated the previous fall (Thomas et al. 1995). The final report on the 1995 spring acoustic survey has not been received from the contractor. Detailed descriptions of their methods and results will be included in the 1996 annual report.

DISCUSSION

Preliminary estimates from the 1995 spawn deposition surveys were incorporated into age structured assessment (ASA) models to project the returning run biomass in 1996 as part of ongoing Department stock assessment and management functions (Funk 1995). ASA modelling generally incorporates other stock abundance estimates including aerial surveys of peak biomass of herring schools and kilometers of visible milt, estimated biomass from fall acoustic surveys, and information about age structure and average fish size to calculate projected returns. During the years of high abundance for herring (1988-1992), spawn deposition surveys provided abundance estimates that varied considerably from these other indicators of population size and spawn deposition estimates were accorded minimal weighting in ASA modelling. In general, differences between spawn deposition survey estimates and other stock assessment methods in 1995 were not as great as in these prior years. Biomass estimation based on spawn deposition surveys in 1995 were somewhat higher than biomass estimates based on aerial surveys of peak abundance, although it is generally

felt that aerial surveys typically tend to underestimate abundance because not all fish schools or milt releases are visible to surveyors.

Accurately estimating the magnitude of herring populations is made difficult because they are a highly mobile species and exhibit large changes in distribution and abundance over a wide range of spatial and temporal scales. Spring spawning migrations provide perhaps the best opportunity to estimate abundance because herring are more aggregated and more visible than at other times of the year. Acoustics and other spectral technologies (e.g. LIDAR, CASI) could provide accurate and cost effective means of quantifying herring abundance, but these methods are limited in the amount of area that can be surveyed and occurrence of herring beyond areas surveyed is difficult to reconcile. Species verification of the quantified targets is also required.

Spawn deposition surveys are designed to estimate spawning abundance for all observed spawning herring, but the accuracy of the method is constrained on several points. It is assumed that all fully recruited age classes spawn annually after recruitment and that all spawning is observed. The extent of incomplete participation in spawning is not known, but surveyors attempt to minimize the occurrence of unobserved spawning through frequent surveys. Two other important factors which can affect the accuracy of spawn deposition estimates are egg loss and calibration of divers. Although estimates of egg loss were not yet possible for the 1995 analysis, this information will become available upon completion of the egg loss study component in June 1996 and previous estimates of biomass can be adjusted using revised loss rates. Revised biomass estimates will continue to provide information useful to fine tuning of ASA population models. Formulation and application of diver calibration models was investigated for this study, and a logical alternative was chosen from among the various possible approaches. Of all terms included in biomass calculations from spawn deposition surveys, diver calibration models may have the greatest potential for affecting population abundance estimates. Investigation of diver calibration models should continue as an integral part of project operations. Because these and other constraints to the accuracy of spawn deposition surveys cannot be cost effectively eliminated, other potential methods of herring stock assessment should continue to be studied in conjunction with spawn surveys. In particular, acoustic surveys during herring spawning migrations may have the potential for estimating spring biomass at lower cost and take advantage of the aggregative behavior of herring at this time of year.

After FY98 a decision will be made to continue either spawn deposition surveys or hydroacoustic biomass estimates of the herring population. The spring 1995 acoustic biomass estimate was 12,000 tonnes while the spawn deposition survey estimate was 16,463 tonnes. The biomass estimation from the acoustic surveys covered only Rocky Bay and Zaikof Bay on Montague Island since these areas represent the primary spawning concentration of herring in PWS. The acoustic surveys generally are conducted prior to spawning when the herring begin to aggregate in the bays where as spawn depositon surveys begin 5 to 7 days after spawning has occurred. In addition to Rocky Bay and Zaikof Bay the herring spawn deposition surveys covered several other sites in the Montague Island summary area. For a

direct comparison between the two methods the acoustic survey may need to be extended to additional spawning areas on Montague Island. During the spring of 1996 acoustic surveys will be conducted in the Montague Island area and compared to the spawn deposition biomass estimates.

CONCLUSIONS

1. Results from the spawn deposition surveys indicated that 18,163 tonnes of herring spawned in Prince William Sound in 1995.

2. Acoustic and spawn deposition techniques indicated that 12,000 and 16,463 tonnes of herring spawned in the Montague Island summary area, respectively.

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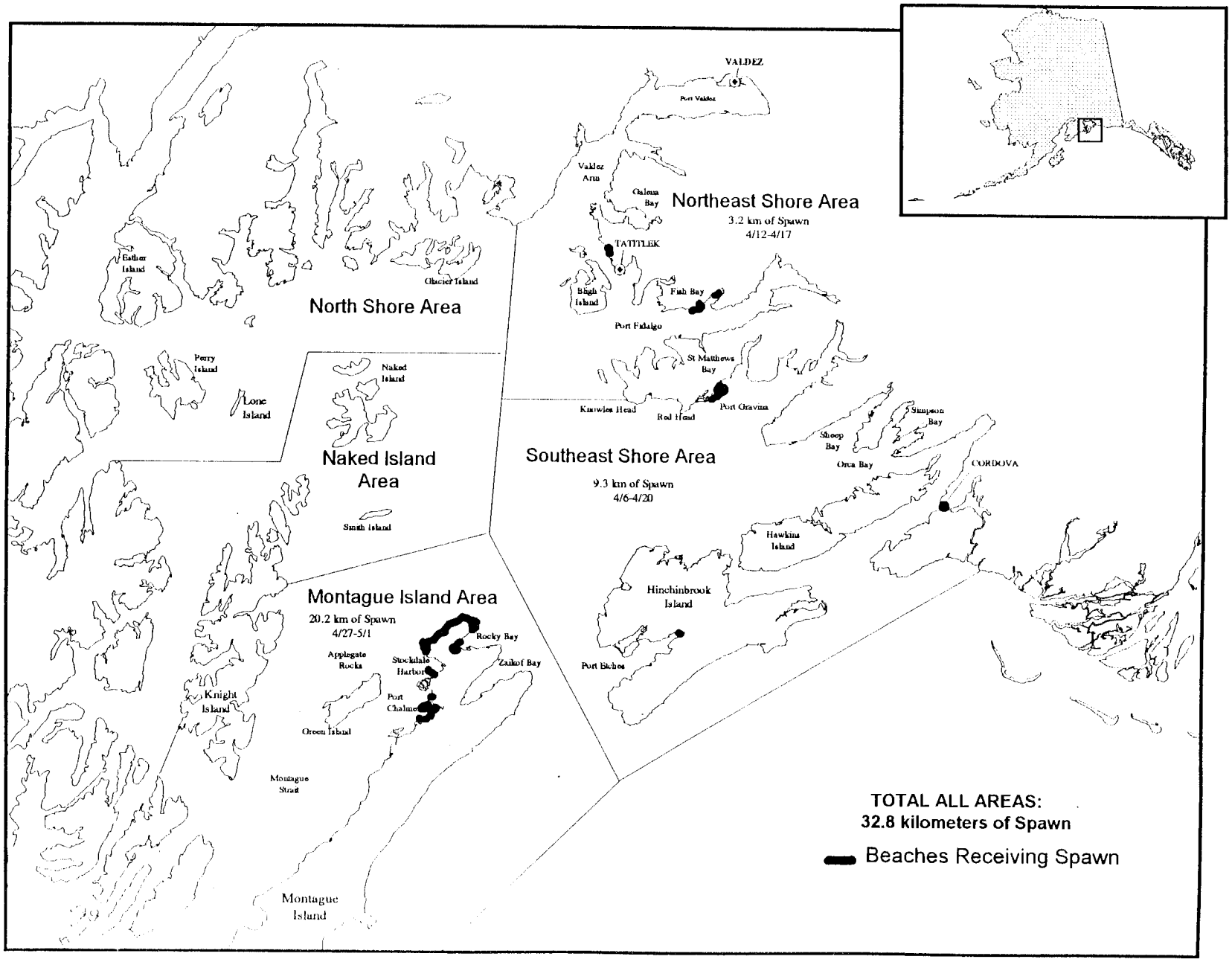


Figure 1. Location of spawning herring and kilometers of shoreline observed during aerial surveys in Prince William Sound, Alaska, 1995.

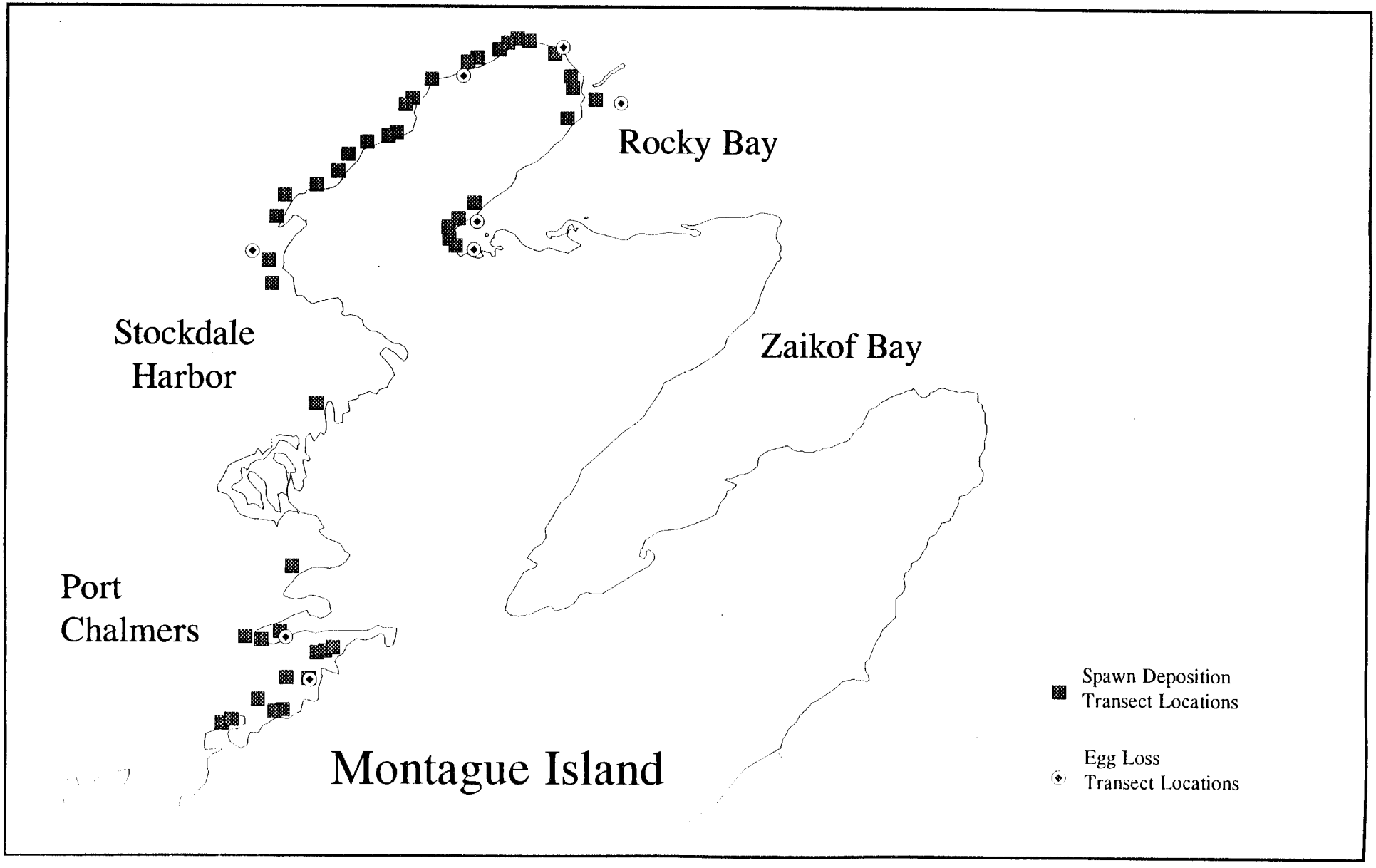


Figure 2. Spawn deposition and egg loss transect locations in the Montague Island summary area, Prince William Sound, Alaska, 1995.

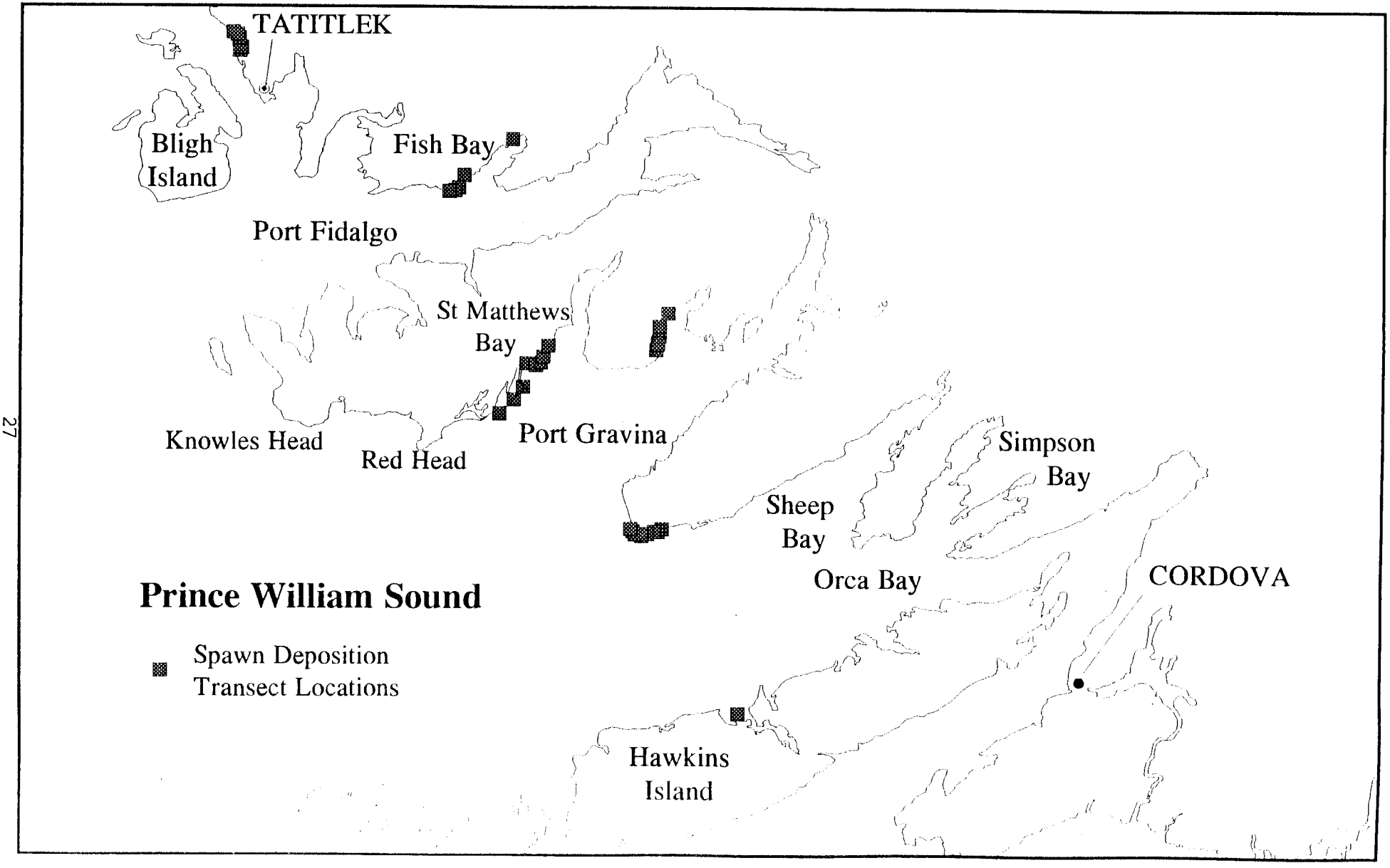


Figure 3. Spawn deposition transects in the Southeastern and Northeastern summary areas, Prince William Sound, Alaska, 1995.

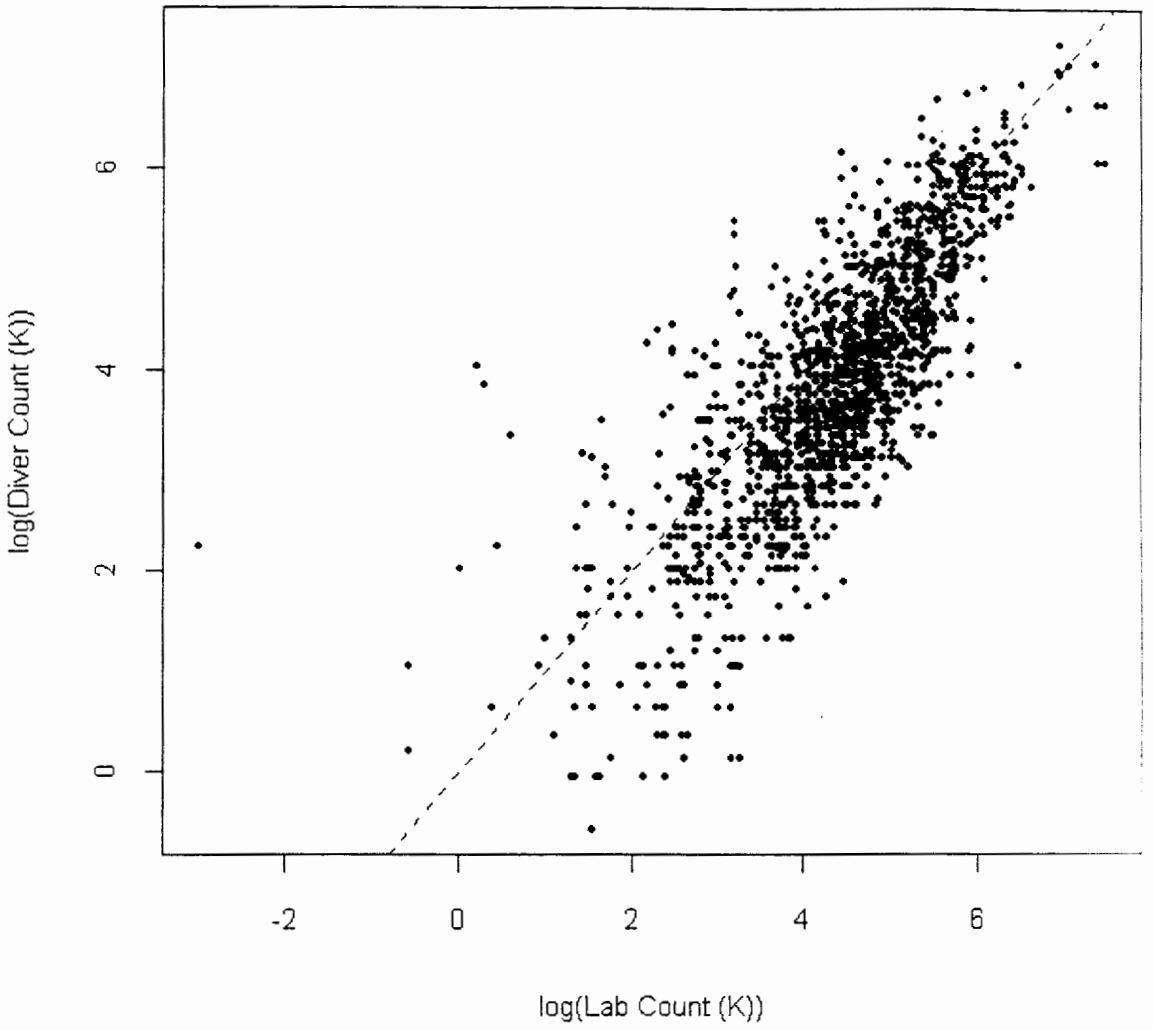
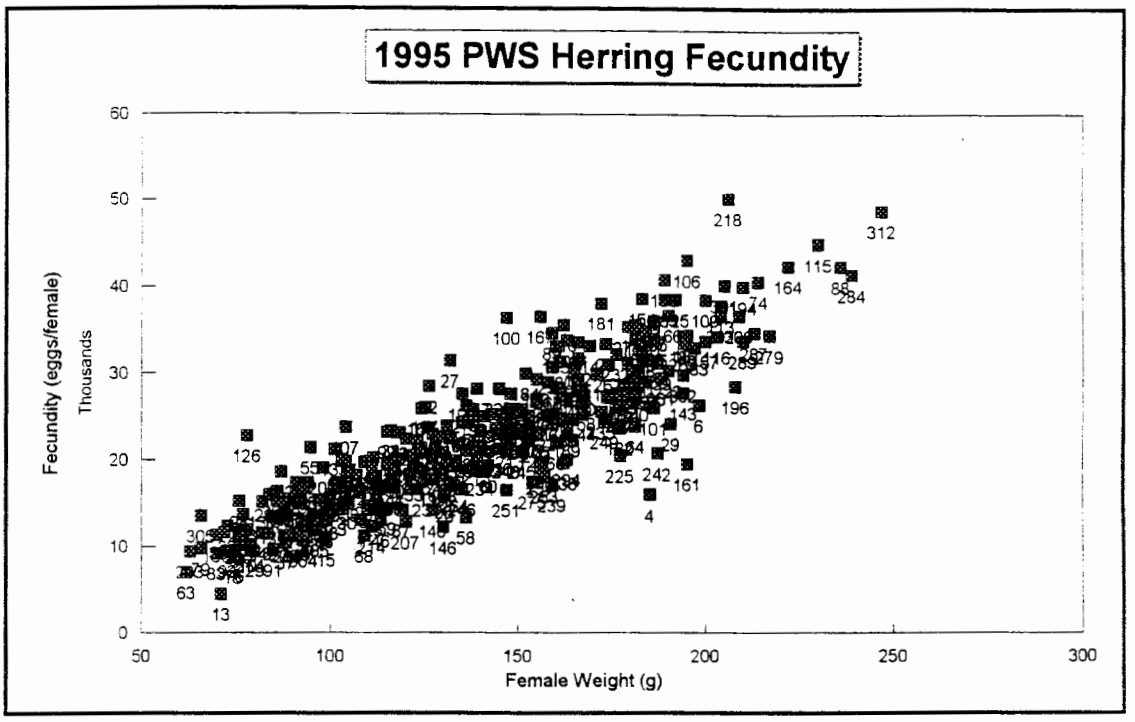


Figure 4: Relationship between diver count and lab count for all divers and all years
Dashed line has intercept = 0 and slope = 1.



Number of Observations	312
Degrees of Freedom	310
Slope of Regression	182.45
Standard Error	6.16
Intercept of Linear Regression	-2531.2
Standard Error of Y Estimate	4345.62
R Squared	0.738

Figure 5. Regression of female weight and number of eggs per female for Pacific herring from Prince William Sound, Alaska, 1995.

Table 1. Location and survey date of herring spawn deposition transects, Prince William Sound, Alaska, 1995.

Summary Area	Transect Location	Transect Number	Date Surveyed
Montague Island	Rocky Bay	51	5/9/95
	Rocky Bay	52	5/11/95
	Rocky Bay	53	5/11/95
	Rocky Bay	54	4/23/95
	Rocky Bay	56	5/11/95
	Rocky Bay	57	5/11/95
	Montague Point	58	5/10/95
	Rocky Bay	59	5/10/95
	Rocky Bay	60	5/11/95
	Montague Point	61	5/10/95
	Montague Point	63	5/9/95
	Montague Point	64	5/9/95
	Montague Point	65	5/8/95
	Graveyard Point	66	5/8/95
	Montague Point	67	5/10/95
	Montague Point	68	5/10/95
	Montague Point	69	5/10/95
	Montague Point	70	5/10/95
	Montague Point	71	5/10/95
	Graveyard Point	72	5/12/95
	Montague Point	73	5/12/95
	Graveyard Point	74	5/13/95
	Graveyard Point	75	5/13/95
	Graveyard Point	76	5/13/95
	Graveyard Point	77	5/15/95
	Graveyard Point	78	5/15/95
	Graveyard Point	79	5/15/95
	Graveyard Point	81	5/8/95
	Graveyard Point	82	5/8/95
	Stockdale Harbor	83	5/15/95
	Stockdale Harbor	84	5/13/95
	Gilmour Pt.	85	5/13/95
	Port Chalmers	86	5/13/95
	Port Chalmers	88	5/13/95
	Port Chalmers	89	5/14/95
	Port Chalmers	90	5/14/95
	Port Chalmers	91	5/14/95
	Port Chalmers	93	5/14/95
	Port Chalmers	94	5/14/95
	Port Chalmers	95	5/14/95

Summary Area	Transect Location	Transect Number	Date Surveyed
Montague Island (continued)	Port Chalmers	96	5/14/95
	Port Chalmers	97	5/13/95
	Port Chalmers	98	5/14/95
	Port Chalmers	99	5/14/95
Southeast	St. Matthews	1	4/20/95
	Hell's Hole	2	4/20/95
	Olsen Bay	3	4/21/95
	Olsen Bay	4	4/21/95
	Hell's Hole	5	4/20/95
	Hell's Hole	6	4/20/95
	St. Matthews	7	4/20/95
	St. Matthews	8	4/20/95
	St. Matthews	9	4/20/95
	St. Matthews	10	4/20/95
	Olsen Bay	11	4/21/95
	Olsen Bay	12	4/21/95
	Olsen Bay	13	4/21/95
	Olsen Bay	14	4/21/95
	Olsen Bay	15	4/21/95
	Olsen Bay	16	4/21/95
	Gravina Pt.	17	4/21/95
	Gravina Pt.	18	4/21/95
	Gravina Pt.	19	4/21/95
	Gravina Pt.	20	4/21/95
	Gravina Pt.	21	4/21/95
	Gravina Pt.	22	4/21/95
	Gravina Pt.	23	4/21/95
	Gravina Pt.	24	4/21/95
	Canoe Passage	35	4/23/95
Northeast	Fish Bay	25	4/22/95
	Fish Bay	26	4/22/95
	Fish Bay	27	4/22/95
	Fish Bay	28	4/22/95
	Fish Bay	29	4/22/95
	Ellamar	30	4/22/95
	Ellamar	31	4/22/95
	Ellamar	32	4/22/95
	Ellamar	33	4/22/95
	Ellamar	34	4/22/95

Table 2. Location and spawn dates for herring egg loss study transects at Montague Island, Prince William Sound, Alaska, 1995.

Transect No.	Location	Date Installed	Date Removed	Number of Site Visits	Spawning Begin	Substrate	Exposure
1	Rocky Bay-Inner	1-May	21-May	12	28-Apr	Boulders	S. facing: semi protected
2	Rocky Bay-Inner	2-May	24-May	12	28-Apr	Rocky	NW facing: protected
11	Montague Reef	1-May	24-May	10	27-Apr	Rocky	SE. facing exposed
14	S. Port Chalmers	4-May	22-May	9	27-Apr	Sand	W. facing: semi protected
13	N. Port Chalmers	4-May	23-May	9	27-Apr	Rocky	NE facing: semi protected
12	N. Graveyard Point	2-May	23-May	12	27-Apr	Rocky	N. facing exposed
9	Graveyard Point	2-May	22-May	9	27-Apr	Rocky	NW facing: exposed
6	Montague Point	30-Apr	21-May	11	27-Apr	Rocky	NE facing: exposed

Table 3. Calculation of spawning herring biomass by project summary area from the spawn deposition surveys in Prince William Sound, Alaska, 1995.

Quantity Estimated	Symbol	Montague	Northeast	Southeast	Total
Statute miles of spawn		12.6	2.0	5.8	20.4
Kilometers of spawn		20.28	3.22	9.33	32.83
Number of possible transects	N	64123	10178	29517	103819
Number of transects sampled	n	52	10	25	87
Number of quadrats sampled	Σm_i	1089	142	302	1533
Proportion of transects sampled	f_1	0.00081	0.00098	0.00085	0.00084
Proportion of quadrats sampled	f_2	0.06325	0.06325	0.06325	0.06325
Average spawn patch width (m)		104.71	71.00	60.40	
Total area of spawn patches (km^2)		2.123	0.229	0.564	2.916
Unweighted average density ($1000/m^2$)		355.66	114.95	122.27	
Average total eggs per transect (K)	$\hat{y}$	14951	2079	2411	
Proportion of eggs lost before survey	R	0.1	0.1	0.1	
Total eggs in area (G)	T	1065.22	23.51	79.06	1167.79
Average herring weight from AWL (g)	$\overline{W}$	123	154	118	
Average weight of females (g)	$\overline{W}_f$	130	160	121	
Number of females in AWL sample	q	839	544	303	
Number of fish in AWL sample		2223	1238	877	
Sex ratio	S	2.650	2.276	2.894	
Fecundity of average female	$F(W_f)$	21,086	26,643	19,419	
Fecundity regression slope		185.239	185.239	185.239	
Fecundity regression intercept		-2995.04	-2995.04	-2995.04	
Tonnes per billion eggs	B'	15.456	13.154	17.588	
Estimated biomass in tonnes	B	16,463.7	309.2	1,390.5	18,163.4
Estimated biomass in short tons		18,148.0	340.9	1,532.7	20,021.5
Short tons per statute mile		1,440.3	170.4	264.3	981.4
Millions of pounds per statute mile		2.88	0.34	0.53	1.96
Distribution (percent miles of spawn)		61.76%	9.80%	28.43%	100.00%
Distribution (percent biomass)		90.64%	1.70%	7.66%	100.00%

Table 4. Variance of calculations of spawning herring biomass from spawn deposition surveys by project summary area, Prince William Sound, Alaska, 1995.

Quantity Estimated	*Symbol*	Montague	Northeast	Southeast	Total
Egg Counts					
Variance - among transects	s_1^2	4.866×10^8	5.202×10^6	1.719×10^7	
Variance - within transects	s_2^2	8.617×10^9	1.182×10^7	1.537×10^8	
Variance - individual quadrats	s_3^2	30295	648	2770	
Variance of estimated total eggs	*Var(T)*	47494	66	739	48300
AWLS Sampling					
Variance of average weight		2.289	2.795	9.497	
Variance of sex ratio	*Var(S)*	0.0052	0.0053	0.0181	
MSE from fecundity regression	s^2	1.787×10^7	1.787×10^7	1.787×10^7	
Mean weight in fecundity sample		139.5	139.5	139.5	
Number of fish in fecundity sample		311	311	311	
Variance of est. average fecundity		8.203×10^4	1.056×10^5	1.289×10^5	
Variance of B'	*Var(B')*	0.257	0.224	0.985	
Biomass Estimate					
Variance of biomass	*Var(B)*	1.163×10^7	1.162×10^4	2.341×10^5	1.187×10^7
Standard error of B	*SE(B)*	3409.5	107.8	483.9	3445.4
Coefficient of variation for B		0.207	0.348	0.348	0.190
95% confidence interval as % of B		40.59%	68.30%	68.21%	37.18%
Confidence limits on estimated biomass					
Lower 95% (tonnes)		9,781.0	98.0	442.1	11,410.4
Upper 95% (tonnes)		23,146.5	520.4	2,338.9	24,916.4
Lower 95% (short tons)		10,781.6	108.0	487.3	12,577.7
Upper 95% (short tons)		25,514.3	573.7	2,578.2	27,465.4

Table 5. Estimated mean weight and length and contributions of each age class to the herring biomass in Prince William Sound, Alaska, 1995.

Year Class	Age Class	Mean Weight (g)	Mean Standard Length (mm)	Biomass by Age Class			
				Weight (tonnes)	Percent by Weight	Number of Fish (x 1,000)	Percent by Number
1994	1			0.0	0.0	0.0	0.0
1993	2	20	163	37.8	0.2	767.4	0.5
1992	3	76	184	2,724.0	15.0	35,679.2	24.1
1991	4	96	197	534.8	2.9	5,597.4	3.8
1990	5	112	208	2,477.2	13.6	22,136.2	15.0
1989	6	133	218	482.3	2.7	3,636.5	2.5
1988	7	144	222	9,568.8	52.7	66,521.0	44.9
1987	8	164	229	170.7	0.9	1,038.4	0.7
1986	9	156	230	241.8	1.3	1,557.8	1.1
1985	10	168	234	824.5	4.5	4,906.9	3.3
1984	11	177	237	1,060.3	5.8	6,002.5	4.1
1983	12	166	236	28.8	0.2	173.0	0.1
1982	13+			0.0	0.0	0.0	0.0
						12,640.2	
Total		123	211	18,151.0	100.0	148,016.2	100.0

APPENDIX A.: DIVER CALIBRATIONS, 1995 SPAWN DEPOSITION SURVEY

1995 herring spawn deposition diver calibration and biomass estimation

by

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Introduction

The 1995 herring spawn deposition survey followed procedures and analyses described in the detailed project description for project number 95166. The diver calibration, however, was done slightly different from that outlined in the DPD. The purpose of the diver calibration was to adjust for systematic biases in the egg count and provide a more accurate estimate. This procedure considered diver and kelp type effects in that different divers may have had very different biases (e.g., one tended to overestimate while another underestimated) and different kelp types may have provided very different conditions for making the estimates. Calibration samples were made throughout the cruise, collected, and counted in the lab. Diver calibration was then determined from the relationship between the divers' counts in the field (dependent variable) and the true lab counts (independent variable), assumed to be without errors. Covariates used in the model were diver and kelp type. Additional factors such as depth of sample, date, and time of day could also be important, but were assumed to be negligible.

Past analyses have used a two-step procedure: (1) pool like groups and (2) obtain calibration parameters for each group. Say we had calibration data for three years for four divers on four different kelp types, for a total of 48 possible groups ($3\times4\times4=48$). The process was to determine which groups could be pooled so that we could "beef up" this years' sample sizes. Lab counts are fairly expensive in time and money making it impossible to collect a sufficient set of calibration samples each year. This process was a way to combine all available data to yield more precise adjustments from the resulting larger sample sizes.

The philosophy of these past analyses was that all years, divers, and kelp types should be assumed to be the same unless we had sufficient evidence to keep them separate. In the procedure described above, the null hypotheses were that factor effects were zero. From looking at the data, it seemed likely that some groups were found to be not different primarily because of small sample sizes, not necessarily because they really were the same. An argument could be made for the philosphy that all divers and kelp types should be assumed to be different and only pooled if we had sufficient evidence that they were the same. From talking with the divers, it seemed that a single diver was more consistent between years than several divers were within the same year. This led to the desire to build separate calibration models for each diver using weighted regression where the weights related to how recent the sample was taken. The current year's data were weighted the heaviest with each preceeding year receiving less and less weight.

Diver Calibration: Methods and Results

Calibration data from all previous years as well as 1995 were extracted from Rbase and MS Excel and imported as a data frame in S-plus. Divers included were bb (Bill Bechtol), bh (Beth Halley), eb (Evelyn Brown), kb (Karl Becker), and mm (Matt Miller). Data for each diver were then separated into individual data frames with a label prefix of '*dc*' for diver calibration followed by the diver's initials. For example, the first few rows of *dc.bb* are as follows:

```
> dc.bb[1:10,]
    year diver veg   est        lab
256   91    bb   1  40.0  20.024390
258   91    bb   4   6.5   4.482627
259   91    bb   3  48.0  46.559540
261   91    bb   3  38.0  41.889230
263   91    bb   4 220.0 134.648300
266   91    bb   2  65.0  49.621430
268   91    bb   4 114.0  52.425000
278   91    bb   3 140.0 207.247600
310   91    bb   4  34.0  65.000000
312   91    bb   2  52.0  80.206670
```

Kelp types were listed as veg and were coded as 1 (eelgrass), 2 (hair kelp), 3 (fucus), or 4 (large brown kelp). Every diver had at least three years worth of calibration data with most divers having four. The number of available calibration samples for each diver, year, and kelp type were as follows:

bh

yr	1	2	3	4
90	19	19	21	25
91	24	42	24	30
92	33	38	26	27
94	6	6	10	13
95	9	9	5	6

bb

yr	1	2	3	4
90	21	5	4	9
91	15	32	17	19
92	28	34	36	28
94	5	5	10	15
95	11	9	7	6

kb

yr	1	2	3	4
91	19	33	23	25
92	34	32	20	23
94	15	9	8	14
95	7	5	8	3

eb

yr	1	2	3	4
88	6	7	7	9
89	19	20	16	26
90	22	25	22	33
91	9	5	9	9
92	35	28	24	24
94	18	7	10	14
95	10	12	8	4

mm

yr	1	2	3	4
92	22	37	32	27
94	6	8	9	15
95	1	5	8	4

As can be seen, the number of samples collected in the past two years has dropped off considerably from previous levels. The intention was to collect 20 samples over a range of densities for each of the four kelp types. No matter what method of calibration is to be used it will be difficult to make reasonably precise adjustments with so few current data.

A series of scatterplots was made for an initial look at the calibration data (Appendix 2). A separate plot was made for each diver, year, and kelp type with the reliability code used as the plotting symbol. A dashed line with a slope of 1 was also added as an aid for viewing the

relationship between diver and lab counts. Points above the line represented overestimation, while points below the line represented underestimation. There seemed to be a tendency to underestimate most of the time. This pattern was fairly consistent for all kelp types and all years. Additionally, the highest egg counts seemed to be clustered closer to the unity line, indicating the possibility that extremely high counts of eggs were more accurate than those from typical densities. For example, diver bb on kelp type 1 in 1995 had five counts in the range of 20,000 to 150,000 eggs that were all somewhat underestimated. Five other counts of approximately 400,000 were extremely accurate with only one of the five not on the unity line itself.

It seemed reasonable to combine a diver's calibration data for all years and run a single regression where the observations were weighted by the year it was collected. Specifically, the weights were calculated as

$$weight_i = \frac{1}{96 - year_i}, \tag{1}$$

where $year_i$ is the year that observation i was taken (95, 94, etc.). The result of this is that observations from 1995 received a weight of 1, while those from 1994 had a weight of ½, those from 1992 had a weight of ¼, etc. This was intuitively appealing in that all data from past years were included in the analysis, but that the most recent data were considered more important or perhaps more relevant to this year's calibration. Separate regressions were fit for each diver with kelp type used as a class variable in the analysis. The S-plus functions used to perform these analyses were *divcal2* and *repar* and are listed in Appendix 1. *Divcal2* was the primary function used to do the weighted regressions, while *repar* was a function called by *divcal2* to do a reparameterization. Arguments passed to *divcal2* were the dataframe to be used (e.g., *dc.bb*) and two logical parameters: one to indicate whether intercept terms were to be included in the model and the other to indicate whether egg counts were to be expressed as eggs or thousands of eggs. Once the model was fit, the function went on to produce residual plots for each year. Arguments passed to *repar* were the dataframe being used, the parameter from *divcal2* to indicate whether an intercept term should be included, and a parameter to indicate whether years should be pooled. The purpose of the reparametrization was to obtain directly relevant parameter estimates. For this analysis, each parameter estimate was the slope for a particular year, rather than having some parameters being the difference in slope between years as would be the case with the usual parameterization. The analyses were run with the intercept forced through zero, egg counts in actual number of eggs (i.e., 100 meant 100 eggs, not 100,000 eggs), and with years pooled. The diver calibration model used was

$$\log(dc_{ijk}) = \beta_{jk} \log(lc_{ijk}) + \varepsilon_{ijk}, \tag{2}$$

where dc_{ijk} was the i^{th} count for diver j on kelp type k and lc_{ijk} was the associated lab count. A summary of the results follows with full results and residual plots included in Appendix 3.

Table 1: Parameter estimates for weighted regression

Diver (j)	Kelp Type (k)	Slope Estimate ($\hat{\beta}_{jk}$)	Standard Error
BB	1 = eelgrass	0.9779	0.0062
	2 = hair kelp	0.9819	0.0062
	3 = fucus	0.9447	0.0066
	4 = large brown kelp	0.9554	0.0068
BH	1 = eelgrass	0.9704	0.0065
	2 = hair kelp	0.9530	0.0059
	3 = fucus	0.9112	0.0067
	4 = large brown kelp	0.9462	0.0064
EB	1 = eelgrass	0.9742	0.0058
	2 = hair kelp	0.9678	0.0061
	3 = fucus	0.9456	0.0067
	4 = large brown kelp	0.9728	0.0066
KB	1 = eelgrass	0.9340	0.0065
	2 = hair kelp	0.9607	0.0068
	3 = fucus	0.9026	0.0074
	4 = large brown kelp	0.9435	0.0074
MM	1 = eelgrass	0.9431	0.0111
	2 = hair kelp	0.9617	0.0079
	3 = fucus	0.9167	0.0079
	4 = large brown kelp	0.9397	0.0082

The egg count adjustment used the appropriate parameter estimate (for a given diver and kelp type) in an inverse prediction method of the form

$$adc_{ijk} = e^{\frac{\log(dc_{ijk})}{\hat{\beta}_{jk}}}, \tag{3}$$

where adc_{ijk} was the i^{th} adjusted count for diver j on kelp type k. Note that the term adc replaced lc in equation (2) to represent the expected lab count, i.e., the adjusted diver count. Using the delta method, the variance for the adjusted count was determined to be as follows:

$$\mathrm{VAR}(adc_{ijk}) = \left(\frac{\log(dc_{ijk})^2 \ \mathrm{VAR}(\hat{\beta}_{jk})}{\hat{\beta}_{jk}^4} \right) e^{\frac{2\log(dc_{ijk})}{\hat{\beta}_{jk}}}. \tag{4}$$

This diver calibration method was implemented with adjusted egg counts calculated for the 1995 data. The range of diver calibration counts for 1995 was 0.6 K to 530 K, while it was 0.6 K to 1442 K for all years. The range of diver estimates on sampled quadrats in 1995 was 0 to 2800 K, almost double the maximum calibration point from any year. This raised the concern that we were using the calibration model on points well outside the range of data used to build the model. We could assume the trend continues to these high counts, but that may not be realistic. As mentioned earlier, there appeared to be a tendency for high counts to be more accurate than moderate counts. This can be seen in a plot of all calibration points where the mean diver count is decidely underestimated below around 5.5 on the X-axis, while points greater than 5.5 appear to be centered on the unity line.

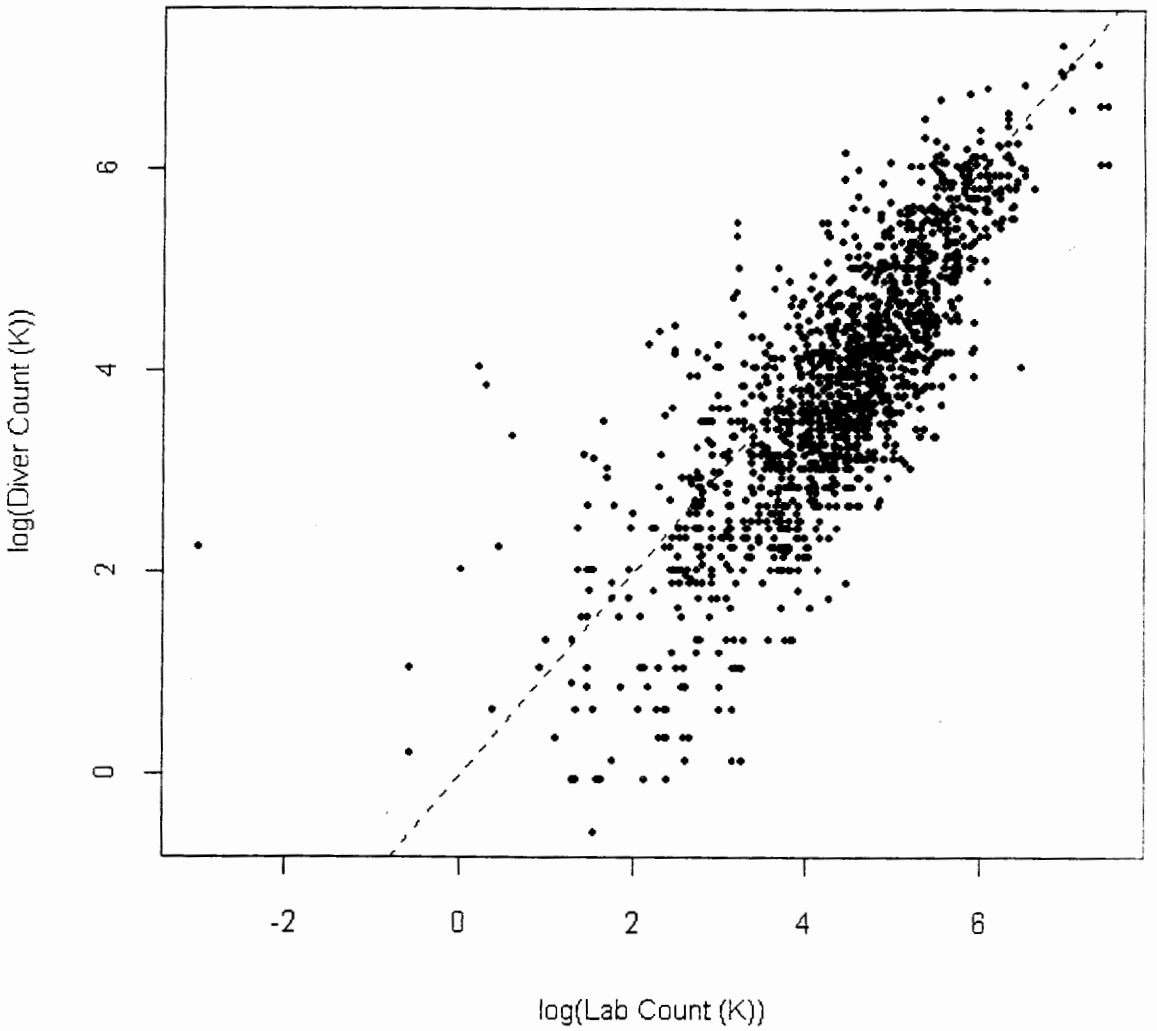

Figure 1: Relationship between diver count and lab count for all divers and all years. Dashed line has intercept = 0 and slope = 1.

Without calibration points to cover the range of the data, it is difficult to model these extreme counts with any kind of certainty. The model over the range of available calibration points resulted in an adjustment that becomes more severe for larger diver estimates. For extremely large estimates, such as 2800 K that is five times the maximum calibration point for 1995, the resulting adjustment would be quite substantial. Based on what little supporting data we have, this does not seem to be realistic.

Several options regarding large diver estimates were considered. The first was to leave the model as it was and run the adjustment. As just stated, this was not considered a realistic option and the resulting five or six extremely large estimates had a substantial effect on the final biomass estimate, varying the result by several thousand tons depending on whether they were included in the analysis or not. The second option was to use the calibration model on diver counts up to some threshold number of eggs, but no adjustment on counts above the threshold. This seemed to be rather drastic to the other extreme. Additionally, there would be an unrealistic discontinuity in the model around the threshold.

A third option was used that was a compromise between the first two. Again, the calibration model was used on diver counts up to a threshold number of eggs. However, instead of switching to the unity line for points above the threshold, a line parallel to the unity line was used that was continuous with the calibration line. The following figure best describes what was done. The resulting calibration tended to follow the apparent curve suggested in Figure 1 where estimates seemed to be more accurate at the higher counts. Perhaps non-linear regression could be used to better model the relationship. More essential, though, is the need for more calibration points for higher diver counts.

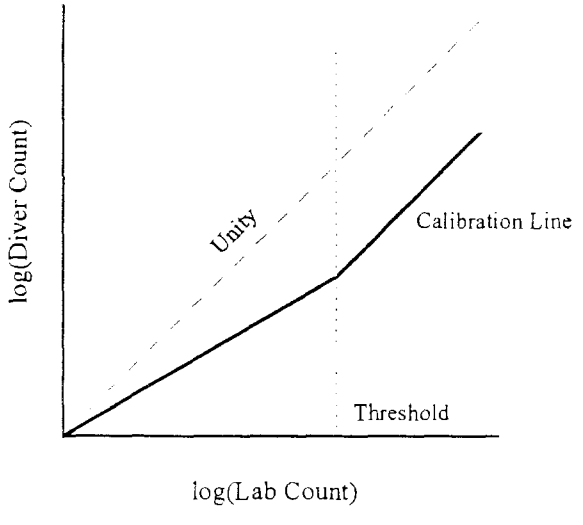

Figure 2: Final calibration adjustment scheme. Unity line has slope = 1, threshold is some determined egg count. The calibration line has a slope determined from multiple linear regression for lab counts less than the threshold and a slope of 1 for greater counts

A threshold of 90 K eggs (log(Lab Count) = 4.5) was chosen based on Figure 1. Putting this in terms of a threshold for the diver counts resulted in a threshold of $\hat{\beta}\log(90{,}000)$. The inverse prediction and variance estimate formulas for counts less than the threshold remained unchanged from equations (3) and (4). The inverse prediction for counts greater than the threshold were simply 90 K plus some constant determined as the difference between the actual diver count and the expected diver count for a lab count of 90 K.

$$adc_{ijk} = e^{\log(90{,}000)+\log(dc_{ijk})-\hat{\beta}\log(90{,}000)} \tag{5}$$

Since in this case a constant was added to the adjusted count for 90 K, the variance estimate would be the same as the variance estimate from equation (4) for a diver count of 90 K.

The resulting calibration models are shown for each diver and kelp type (Figure 3). The size of the plotting symbol represents its weight in the linear regression, i.e., the largest symbols are from 1995, etc. Again, there may well be better ways to model this relationship. Some sort of non-linear regression should be explored as well as spline regression. For the time being, this seemed to be a reasonable and workable approach. To fully model these extremes in the data, we are absolutely going to need some data in these ranges. Without that, it is purely guesswork.

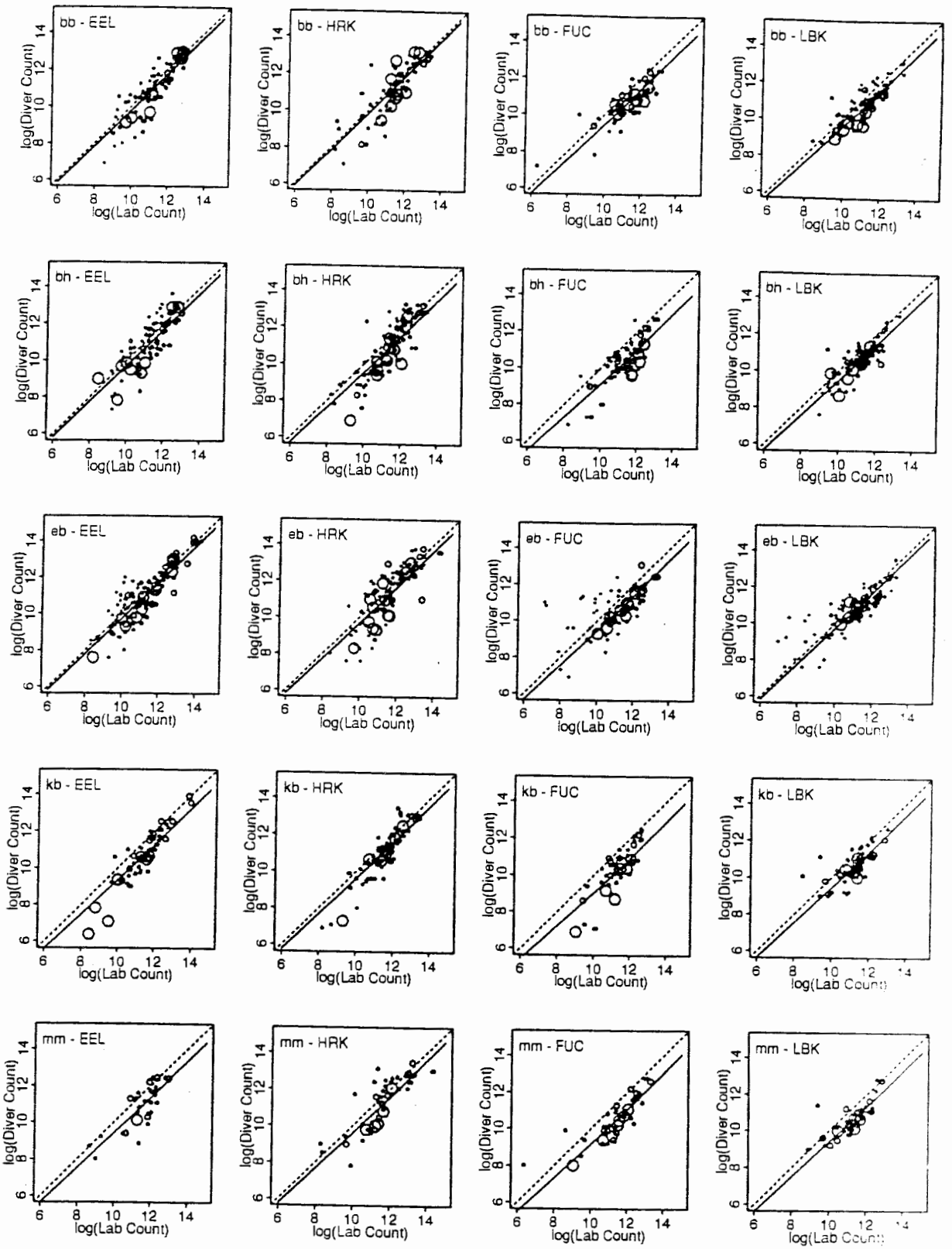

Figure 3: Calibration model curves for each diver and kelp type combination. Size of plotting symbol represents weight in the linear regression analysis.

Biomass Estimation: Methods and Results

Egg count adjustments were made for all diver counts from all samples: single visit transects, repeated visit transects, deca-frame sites, and predator exclusion frames. Single visit transects were used to estimate total herring biomass in areas designated Northeast PWS, Southeast PWS and Montague Island. An initial three-stage process was used to finalize the data set.

(1) Several transects had leading or trailing quadrats with egg counts of zero. Since the length of a transect was used to calculate spawn patch width, these quadrats needed to be removed. The S-plus function *trim* was used to do this (Appendix 1).

(2) Frequently, piles of loose eggs and eggs on detached vegetation were washed up on shore a long way from attached vegetation and the spawn patch itself. These piles were included in the transects where they existed and were recorded as vegetation *win* or wind row. Usually there was a long gap with no eggs between the wind row and the spawn patch. It was felt that these empty quadrats should not be included in the sample as they would falsely inflate the patch width. A protocol was determined whereby empty quadrats were deleted when there were four or more of them in a row following wind row. These quadrats were deleted manually in a text editor.

(3) Each quadrat was identified with a primary vegetation code as defined in the database documentation. Each of these codes related to one of four kelp types, corresponding to the four types used in the diver calibration. A column was added to the dataframe to indicate the kelp type, which together with the diver, specified which egg count adjustment to use.

The final dataset was read into an S-plus data frame called *herring*, a portion of which follows:

```
> herring[1:10,]
   year transect station veg eggs loose left diver      area kelp
1    95        1       1 win 0.04  0.00    0    bb Southeast  FUC
2    95        1      18 bfr 0.00  0.05    0    bb Southeast  HRK
3    95        1      19 sd  0.00  0.00    0    bb Southeast  EEL
4    95        1      20 sd  0.00  0.00    0    bb Southeast  EEL
5    95        1      21 ul  0.00  0.00    0    bb Southeast  LBK
6    95        1      22 ul  0.00  0.00    0    bb Southeast  LBK
7    95        1      23 rib 0.00  0.00    0    bb Southeast  LBK
8    95        1      24 rib 0.00  0.00    0    bb Southeast  LBK
9    95        1      25 rib 0.00  0.00    0    bb Southeast  LBK
10   95        1      26 cob 0.00  0.00    0    bb Southeast  FUC
```

Once the data were finalized, a series of S-plus functions was used to do the biomass estimation (Appendix 1). The function *adjust* did the actual adjustment on the diver egg counts. Arguments were the dataframe (*herring*) and a logical variable to set whether the high count adjustment was to be done. If so, the term *limit* within the function set the threshold (90,000). The output of this function was input to the *by.transect* function, which did calculations at the transect level. The output of this was then input to the *by.area* function, which did the final calculations for each area. Lastly, this output was input to the function *total*, which did all

necessary calculations to produce the standard summary output obtained in past years. This output includes appropriate statistics for each area separately as well as for all areas combined. The S-plus functions can be used in a couple ways. Each step can be done separately with the output from each saved and then input to the next function:

```
herring.by.transect <- by.transect(herring)
herring.by.area <- by.area(herring.by.transect)
herring.total <- total(herring.by.area)
```

Alternately, the functions can be nested and performed in one step:

```
herring.total <- total(by.area(by.transect(herring)))
```

Table 2a: Summary of Prince William Sound Herring Egg Deposition Survey for 1995

Quantity Estimated	Symbol	Montague	Northeast	Southeast	Total
Statute miles of spawn		12.6	2.0	5.8	20.4
Kilometers of spawn		20.28	3.22	9.33	32.83
Number of possible transects	N	64123	10178	29517	103819
Number of transects sampled	n	52	10	25	87
Number of quadrats sampled	Σm_i	1089	142	302	1533
Proportion of transects sampled	f_1	0.00081	0.00098	0.00085	0.00084
Proportion of quadrats sampled	f_2	0.06325	0.06325	0.06325	0.06325
Average spawn patch width (m)		104.71	71.00	60.40	
Total area of spawn patches (km^2)		2.123	0.229	0.564	2.916
Unweighted average density ($1000/m^2$)		355.66	114.95	122.27	
Average total eggs per transect (K)	$\hat{y}$	14951	2079	2411	
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Average weight of females (g)	$\overline{W}_f$	130	160	121	
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Number of fish in AWL sample		2223	1238	877	
Sex ratio	S	2.650	2.276	2.894	
Fecundity of average female	$F(W_f)$	21086	26643	19419	
Fecundity regression slope		185.239	185.239	185.239	
Fecundity regression intercept		-2995.04	-2995.04	-2995.04	
Tonnes per billion eggs	B'	15.456	13.154	17.588	
Estimated biomass in tonnes	B	16463.7	309.2	1390.5	18163.4
Estimated biomass in short tons		18148.0	340.9	1532.7	20021.5
Short tons per statute mile		1440.3	170.4	264.3	981.4
Millions of pounds per statute mile		2.88	0.34	0.53	1.96
Distribution (percent miles of spawn)		61.76%	9.80%	28.43%	100.00%
Distribution (percent biomass)		90.64%	1.70%	7.66%	100.00%

Table 2b: Variances of Egg Deposition Survey Estimates for 1995

Quantity Estimated	*Symbol*	Montague	Northeast	Southeast	Total
Egg Counts					
Variance - among transects	s_1^2	4.866×10^8	5.202×10^6	1.719×10^7	
Variance - within transects	s_2^2	8.617×10^9	1.182×10^7	1.537×10^8	
Variance - individual quadrats	s_3^2	30295	648	2770	
Variance of estimated total eggs	*Var(T)*	47494	66	739	48300
AWLS Sampling					
Variance of average weight		2.289	2.795	9.497	
Variance of sex ratio	*Var(S)*	0.0052	0.0053	0.0181	
MSE from fecundity regression	s^2	1.787×10^7	1.787×10^7	1.787×10^7	
Mean weight in fecundity sample		139.5	139.5	139.5	
Number of fish in fecundity sample		311	311	311	
Variance of est. average fecundity		8.203×10^4	1.056×10^5	1.289×10^5	
Variance of B′	*Var(B′)*	0.257	0.224	0.985	
Biomass Estimate					
Variance of biomass	*Var(B)*	1.163×10^7	1.162×10^4	2.341×10^5	1.187×10^7
Standard error of B	*SE(B)*	3409.5	107.8	483.9	3445.4
Coefficient of variation for B		0.207	0.348	0.348	0.190
95% confidence interval as % of B		40.59%	68.30%	68.21%	37.18%
Confidence limits on estimated biomass					
Lower 95% (tonnes)		9781.0	98.0	442.1	11410.4
Upper 95% (tonnes)		23146.5	520.4	2338.9	24916.4
Lower 95% (short tons)		10781.6	108.0	487.3	12577.7
Upper 95% (short tons)		25514.3	573.7	2578.2	27465.4

Appendix 1: S-plus Functions

```
divcal2_function(df,I=T,K=F) {

if(!K) { df$est_df$est*1000; df$lab_df$lab*1000 }
fit_lm(log(df$est)~-1+repar(df,I,vy=F),na.action=na.omit,singular.ok=T,weight=1/(96-df$year))
u.y_sort(unique(df$year))
if(length(u.y)==7 | length(u.y)==8) par(mfrow=c(2,4))
if(length(u.y)==5 | length(u.y)==6) par(mfrow=c(2,3))
if(length(u.y)==3 | length(u.y)==4) par(mfrow=c(2,2))
if(length(u.y)==2) par(mfrow=c(1,2))
par(mgp=c(2,1,0),omi=rep(0.5,4),mar=c(5,3,2,2))
x.max_max(fitted(fit),na.rm=T); x.min_min(fitted(fit),na.rm=T)
y.max_max(abs(resid(fit)),na.rm=T)

for(y in u.y) {
        ind_df$year==y
        plot(fitted(fit)[ind],resid(fit)[ind],xlim=c(x.min,x.max),ylim=c(-y.max,y.max),
                xlab=paste("Fitted Values -",1900+y),ylab="Residuals",type="n",cex=0.65)
        abline(0)
        text(fitted(fit)[ind],resid(fit)[ind],df$veg[ind],cex=0.5)
        }
mtext(paste("Residual plots for",substring(deparse(substitute(df)),4)),side=1,line=-
2,outer=T,adj=1,cex=0.7)
par(mfrow=c(1,1))
return(summary(fit,F))
}
```

```
repar_function(df,int=T,vy=T) {

attach(df,2)
if(vy) x_veg*10 + year%%10
       else x_veg
u.x <- sort(unique(x))
tmp <- matrix(x, nrow = length(u.x), ncol = length(x), byrow = T)
i1 <- t(tmp == u.x) * 1
dimnames(i1) <- list(dimnames(x)[[1]], paste("i", u.x, sep = ""))

i2_i1*log(lab)
dimnames(i2)[[2]] <- paste("s", u.x, sep = "")
detach(2)

if(int) {
        imat_numeric(0)
        for(col in 1:ncol(i1)) {
                tmp_dimnames(imat)[[2]]
                imat_cbind(imat,i1[,col],i2[,col])
                dimnames(imat)_list(NULL,c(tmp,paste(c("i","s"),u.x[col],sep="")))
                }
        return(imat)
        }
else return(i2)
}
```

Appendix 1: continued

```
trim_function(df) {

ord_order(df$transect,df$station)
df_df[ord,]

df$eggs[is.na(df$eggs)]_0; df$loose[is.na(df$loose)]_0; df$left[is.na(df$left)]_0
eggs_df$eggs+df$loose+df$left
ind_!duplicated(df$transect)
first_c((1:nrow(df))[ind],nrow(df)+1)
keep_rep(T,nrow(df))

for(trans in first) {

        if(trans<nrow(df)+1) {
                i_trans
                while(eggs[i]==0 & i<=nrow(df)) { keep[i]_F; i_i+1 }
                }

        if(trans>1) {
                i_trans-1
                while(eggs[i]==0 & i>=1) { keep[i]_F; i_i-1 }
                }

        }

return(df[keep,])
}
```

```
adjust_function(df,high.adj=F) {

attach(df,2)

d_c(rep("bb",5),rep("bh",5),rep("eb",5),rep("kb",5),rep("mm",5))
k_rep(c("EEL","HRK","FUC","LBK","NA"),5)
s_c(.9779,.9819,.9447,.9554,1,
    .9704,.9530,.9112,.9462,1,
    .9742,.9678,.9456,.9728,1,
    .9340,.9607,.9026,.9435,1,
    .9431,.9617,.9167,.9397,1)
v_c(.0062,.0062,.0066,.0068,0,
    .0065,.0059,.0067,.0064,0,
    .0058,.0061,.0067,.0066,0,
    .0065,.0068,.0074,.0074,0,
    .0111,.0079,.0079,.0082,0)
v_v^2

pos1_match(paste(as.character(diver),as.character(kelp)),paste(d,k))
slope_s[pos1]; variance_v[pos1]

eggs[is.na(eggs)]_0; loose[is.na(loose)]_0; left[is.na(left)]_0
est_(eggs+left)*1000
adjegg_rep(0,nrow(df))
```

Appendix 1: continued

```
ind_est>0
adjegg[ind]_exp(log(est[ind])/slope[ind])  # estimates for egg count < limit
varegg_rep(0,nrow(df))
varegg[ind]_(adjegg[ind]^2)*((log(est[ind]))^2)*variance[ind]/(slope[ind]^4)

if(high.adj) {
        limit_90000
        ind_adjegg>limit
        adjegg[ind]_exp(log(limit)+log(est[ind])-slope[ind]*log(limit)) # egg count > limit
        varegg[ind]_exp(2*log(limit)/slope[ind])*((log(limit))^2)*variance[ind]/(slope[ind]^4)
        }

adjtot_adjegg/1000+loose
varegg_varegg/1e6

detach(2)
return(data.frame(df,adjtot,varegg))
}
```

```
by.transect_function(df) {

year_tapply(df$year,df$transect,unique)
transect_tapply(df$transect,df$transect,unique)
diver_tapply(df$diver,df$transect,unique)
area_tapply(df$area,df$transect,unique)

length.na_function(x) { sum(!is.na(x)) }
mi_tapply(df$station,df$transect,length.na)
wi_mi*5
Mi_wi/sqrt(0.1)
f2_mi/Mi; f2[is.na(f2)]_mean(f2,na.rm=T)

yi.bar_tapply(df$adjtot,df$transect,sum)/mi; yi.bar[is.na(yi.bar)]_0
yi.hat_Mi*yi.bar
pos_tapply(df$adjtot,df$transect)
s3i_tapply(df$varegg,df$transect,sum)
ss_(df$adjtot-yi.bar[pos])^2
s2i_tapply(ss,df$transect,sum)

return(data.frame(year,transect,diver,area,mi,wi,Mi,f2,yi.bar,yi.hat,s3i,s2i))
}
```

```
by.area_function(df) {

df$area_as.character(df$area)
areas_c("Montague","Southeast","Northeast","Total")
miles_c(12.6,5.8,2.0,20.4)
kmeter_miles*1.609344

year_tapply(df$year,df$area,unique)
area_tapply(df$area,df$area,unique)
R_rep(0.10,length(area))
n_tapply(df$transect,df$area,length)
```

Appendix 1: continued

```
mi.of.spawn_miles[match(as.character(area),areas)]
km.of.spawn_kmeter[match(as.character(area),areas)]
N_km.of.spawn*1000/sqrt(0.1)
mean.w_tapply(df$wi,df$area,mean)
spawn.area_km.of.spawn*mean.w/1000
avg.density_tapply(df$yi.bar*10,df$area,mean)

y.hat_tapply(df$yi.hat,df$area,sum)/n
T.est_N*y.hat*1e-6/(1-R)

s3_tapply(df$s3i,df$area,sum)
ind_df$mi>1
s2_tapply(df$Mi[ind]^2*df$s2i[ind]/(df$mi[ind]-1),df$area[ind],sum)/n
pos_tapply(df$yi.hat,df$area)
ss_(df$yi.hat-y.hat[pos])^2
s1_tapply(ss,df$area,sum)/(n-1)
f1_n/N
f2_tapply(df$f2,df$area,mean)
sum.mi_tapply(df$mi,df$area,sum)

T.var_N^2*1e-12*((1-f1)*s1/n + f1*(1-f2)*s2/sum.mi + f1*f2*s3/sum.mi)/(1-R)^2

point.est_data.frame(year,mi.of.spawn,km.of.spawn,N,n,sum.mi,f1,f2,mean.w,spawn.area,avg.density,y.hat
,R,T.est)
var.est_data.frame(s1,s2,s3,T.var)

w.bar_c(123,154,118)
wf.bar_c(130,160,121)
n.fish_c(2223,1238,877)
n.female_c(839,544,303)
w.bar.var_c(40^2/699,30^2/322,41^2/177)
fec.mse_rep((4227.147)^2,length(area))
fec.wf.bar_rep(139.499,length(area)); sum.wt2_rep(6543458.35,length(area));
fec.n_rep(311,length(area))
fec.slope_rep(185.239,length(area)); fec.int_rep(-2995.04,length(area))

sex.ratio_n.fish/n.female
sex.ratio.var_sex.ratio^2*(sex.ratio-1)/n.fish
avg.fec_fec.int+fec.slope*wf.bar
avg.fec.var_fec.mse*( 1/fec.n + 1/n.female + (wf.bar-fec.wf.bar)^2/(sum.wt2-fec.n*fec.wf.bar^2) )

B.prime_w.bar*sex.ratio*1e3/avg.fec
B.prime.var_1e6*((sex.ratio/avg.fec)^2*w.bar.var + (w.bar/avg.fec)^2*sex.ratio.var +
(w.bar*sex.ratio/avg.fec^2)^2*avg.fec.var )

B_T.est*B.prime
B.var_T.est^2*B.prime.var + B.prime^2*T.var - T.var*B.prime.var
B.se_sqrt(B.var); B.cv_B.se/B

B.short_B*1.1023; ton.per.mile_B.short/mi.of.spawn; Mlb.per.mile_ton.per.mile*2e-3
percent.miles_100*mi.of.spawn/sum(mi.of.spawn); percent.biomass_100*B/sum(B)

tonnes.lower_B-1.96*B.se; tonnes.upper_B+1.96*B.se
short.lower_tonnes.lower*1.1023; short.upper_tonnes.upper*1.1023
percent.B_100*1.96*B.cv
```

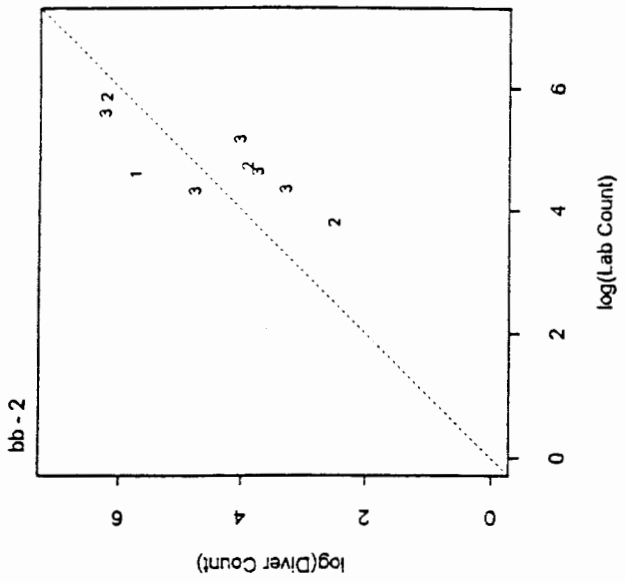
Appendix 1: continued

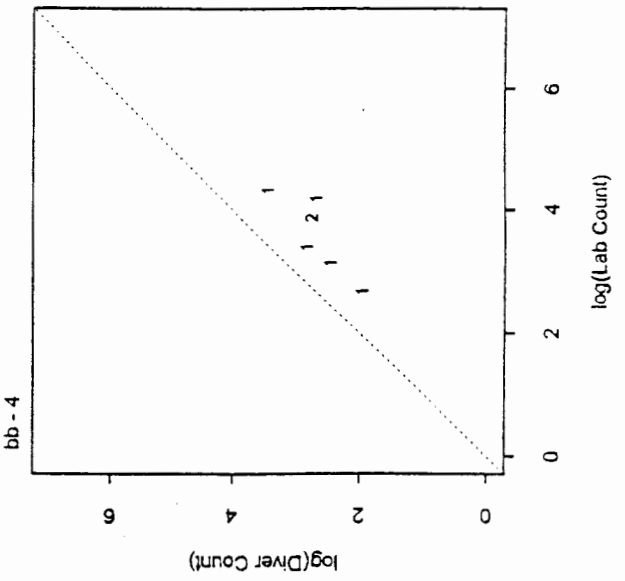
```
point.est_data.frame(point.est,w.bar,wf.bar,n.female,n.fish,sex.ratio,avg.fec,fec.slope,fec.int,B.prim
e,B,B.short,ton.per.mile,Mlb.per.mile,percent.miles,percent.biomass)
var.est_data.frame(var.est,w.bar.var,sex.ratio.var,fec.mse,fec.wf.bar,sum.wt2,fec.n,avg.fec.var,B.prim
e.var,B.var,B.se,B.cv,percent.B,tonnes.lower,tonnes.upper,short.lower,short.upper)

return(point.est,var.est)
}
```

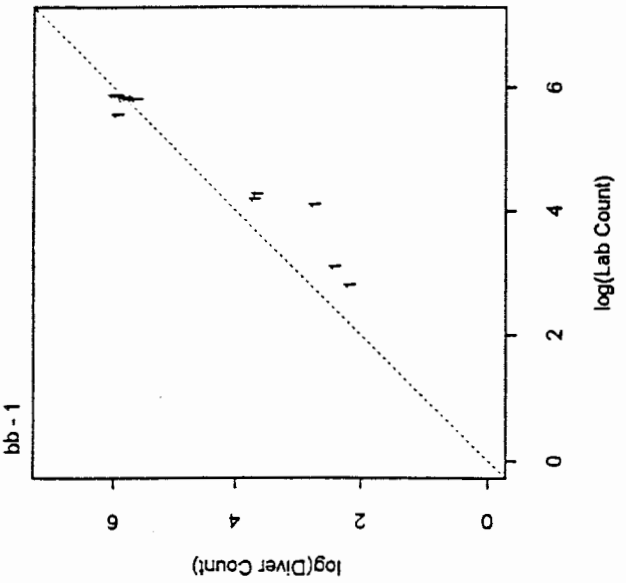
```
total_function(df) {

r_nrow(df$point.est)+1
attach(df$point.est,2)
year[r]_mean(year); mi.of.spawn[r]_sum(mi.of.spawn); km.of.spawn[r]_sum(km.of.spawn); N[r]_sum(N);
n[r]_sum(n)
sum.mi[r]_sum(sum.mi); f1[r]_n[r]/N[r]; f2[r]_mean(f2); mean.w[r]_NA; spawn.area[r]_sum(spawn.area);
avg.density[r]_NA
y.hat[r]_NA; R[r]_NA; T.est[r]_sum(T.est); w.bar[r]_NA; wf.bar[r]_NA; n.female[r]_NA; n.fish[r]_NA;
sex.ratio[r]_NA
avg.fec[r]_NA; fec.slope[r]_NA; fec.int[r]_NA; B.prime[r]_NA; B[r]_sum(B); B.short[r]_1.1023*B[r]
ton.per.mile[r]_B.short[r]/mi.of.spawn[r]; Mlb.per.mile[r]_ton.per.mile[r]*2e-3;
percent.miles[r]_sum(percent.miles); percent.biomass[r]_sum(percent.biomass)

point.est_data.frame(year,mi.of.spawn,km.of.spawn,N,n,sum.mi,f1,f2,mean.w,spawn.area,avg.density,y.hat
,R,T.est,

w.bar,wf.bar,n.female,n.fish,sex.ratio,avg.fec,fec.slope,fec.int,B.prime,B,B.short,ton.per.mile,Mlb.pe
r.mile,
        percent.miles,percent.biomass)
dimnames(point.est)[[1]][r]_"Total"
detach(2)

attach(df$var.est,2)
s1[r]_NA; s2[r]_NA; s3[r]_NA; T.var[r]_sum(T.var); w.bar.var[r]_NA; sex.ratio.var[r]_NA;
fec.mse[r]_NA; fec.wf.bar[r]_NA
sum.wt2[r]_NA; fec.n[r]_NA; avg.fec.var[r]_NA; B.prime.var[r]_NA; B.var[r]_sum(B.var);
B.se[r]_sqrt(B.var[r])
B.cv[r]_B.se[r]/B[r]; percent.B[r]_100*1.96*B.cv[r]; tonnes.lower[r]_B[r]-1.96*B.se[r];
tonnes.upper[r]_B[r]+1.96*B.se[r]
short.lower[r]_tonnes.lower[r]*1.1023; short.upper[r]_tonnes.upper[r]*1.1023

var.est_data.frame(s1,s2,s3,T.var,w.bar.var,sex.ratio.var,fec.mse,fec.wf.bar,sum.wt2,fec.n,avg.fec.var
,
        B.prime.var,B.var,B.se,B.cv,percent.B,tonnes.lower,tonnes.upper,short.lower,short.upper)
dimnames(var.est)[[1]][r]_"Total"
detach(2)

return(point.est,var.est)
}
```

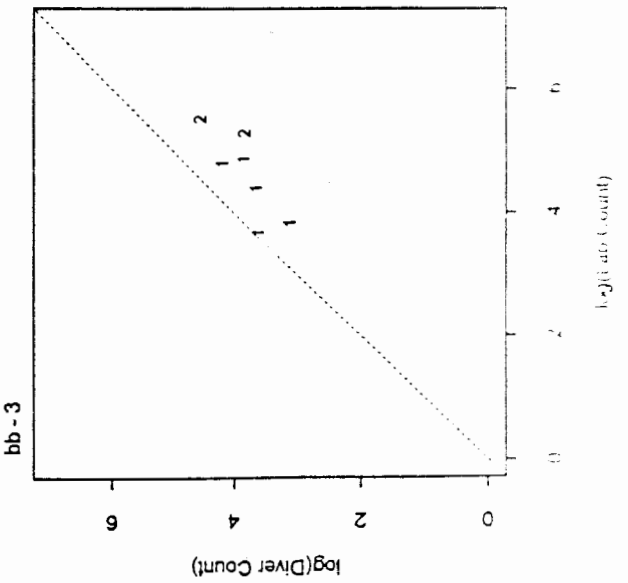
Appendix 2: Individual scatterplots

Year 1995 – Diver bb



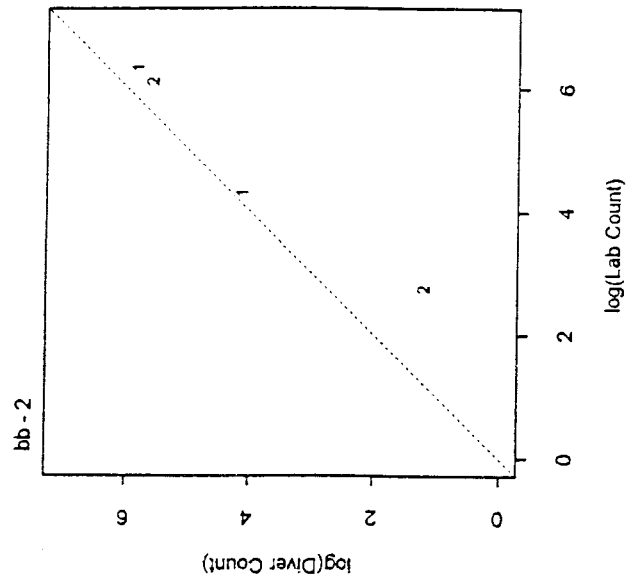


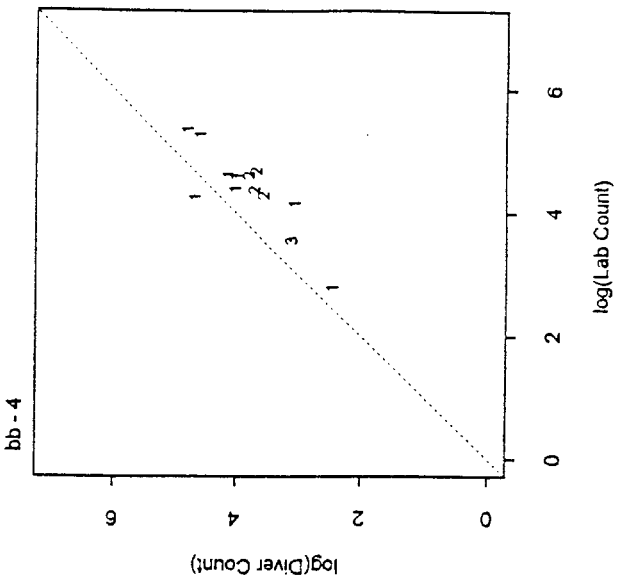


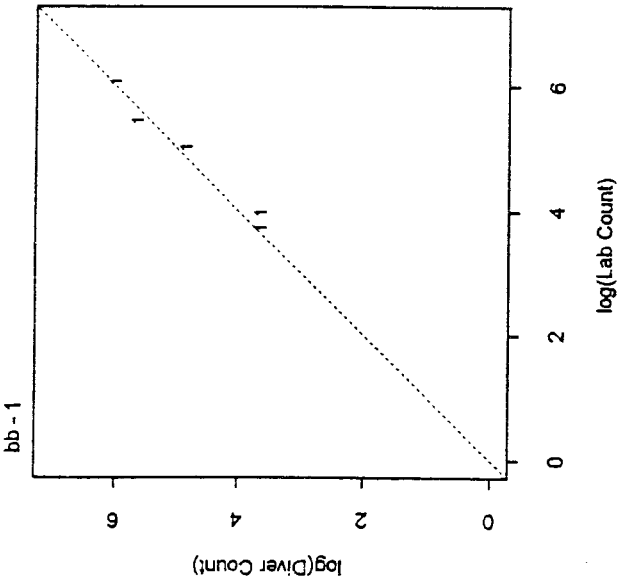


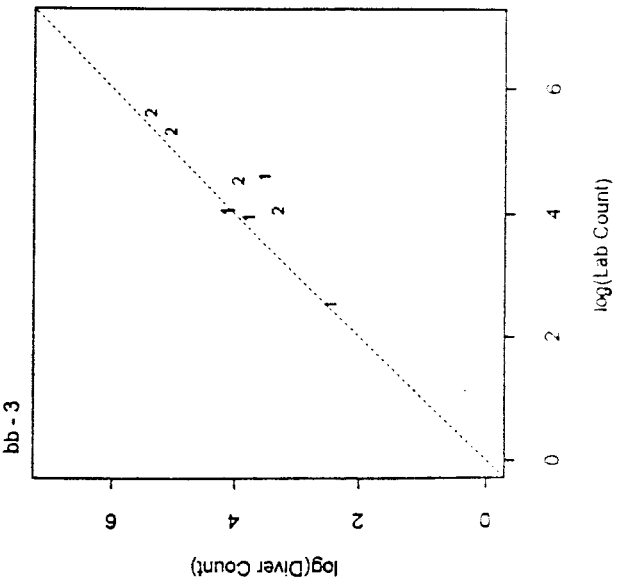
Appendix 2: continued

Year 1994 – Diver bb



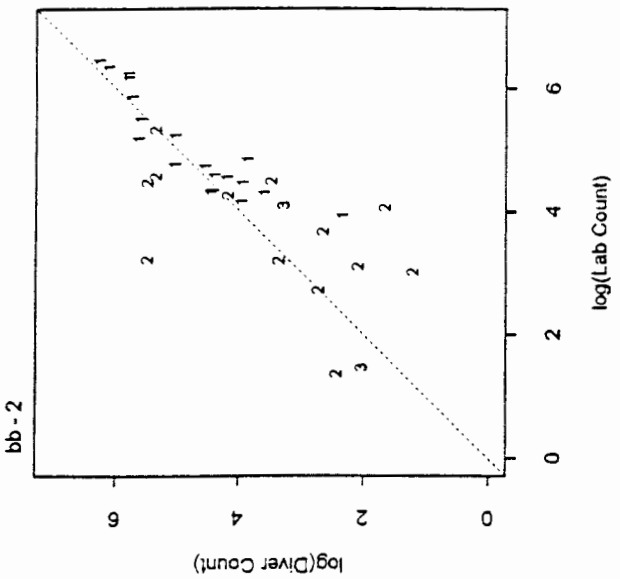


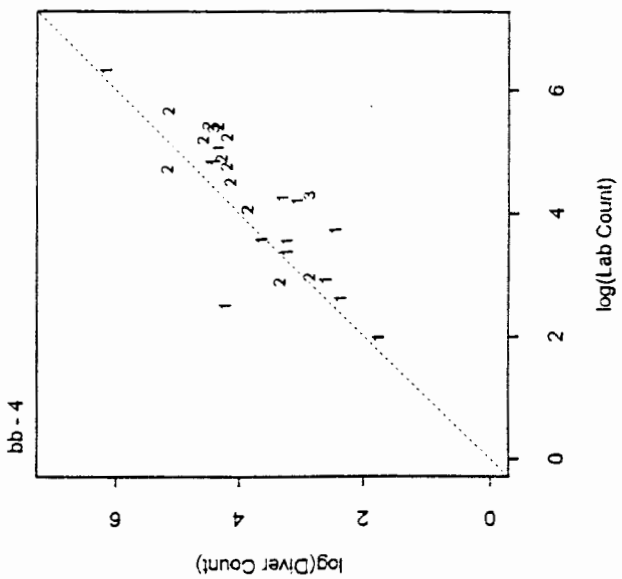


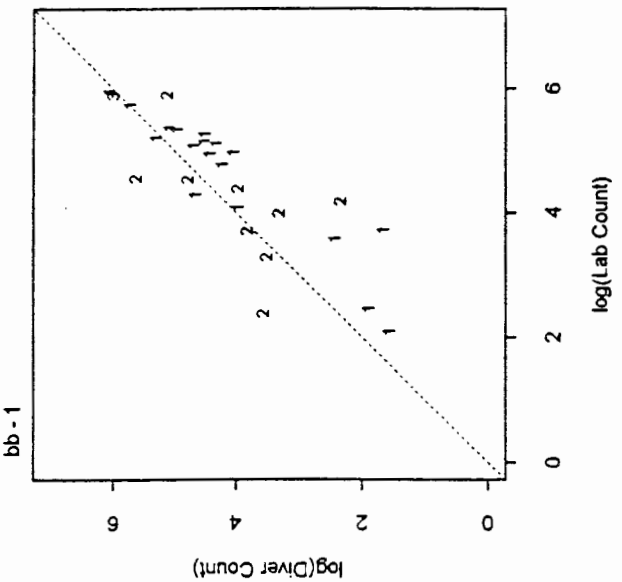


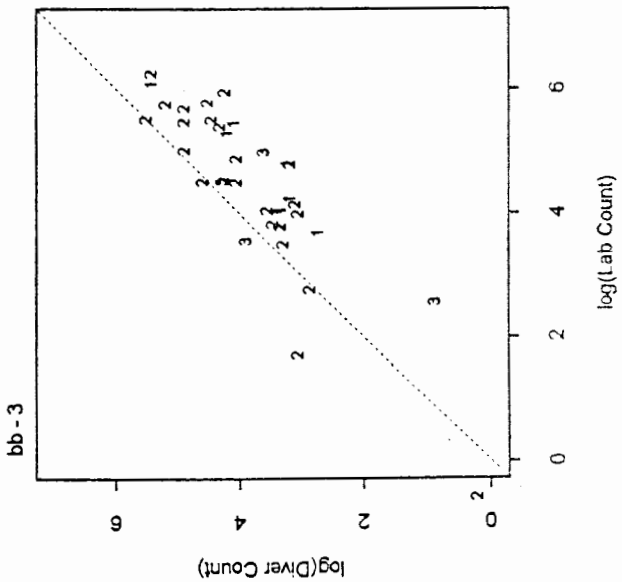
Appendix 2: continued

Year 1992 – Diver bb



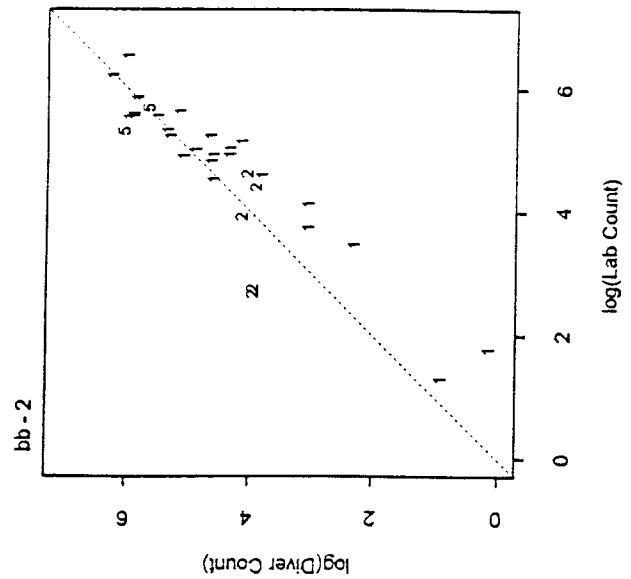


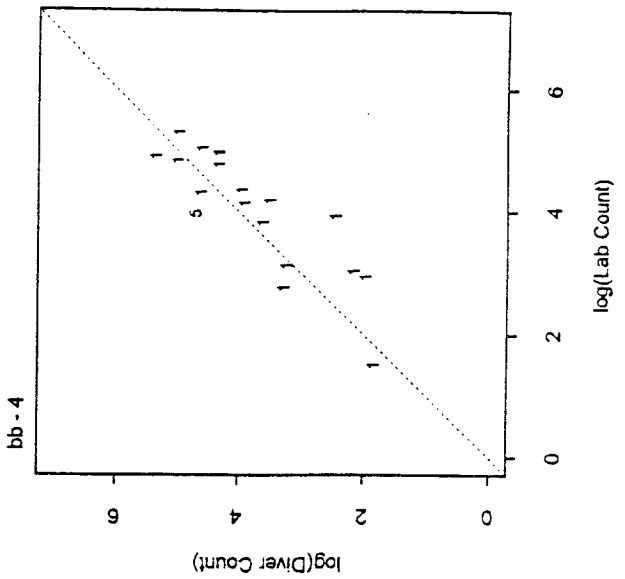


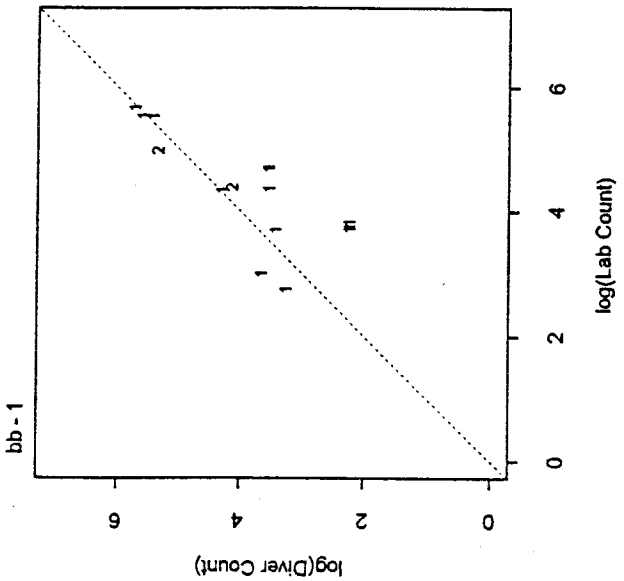


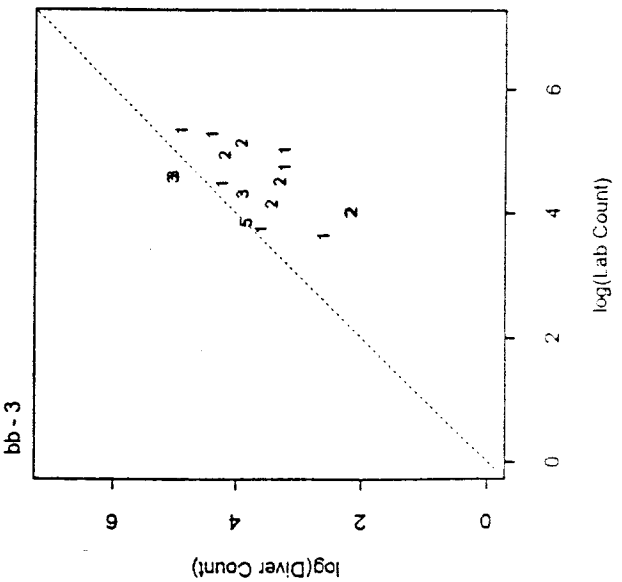
Appendix 2: continued

Year 1991 – Diver bb



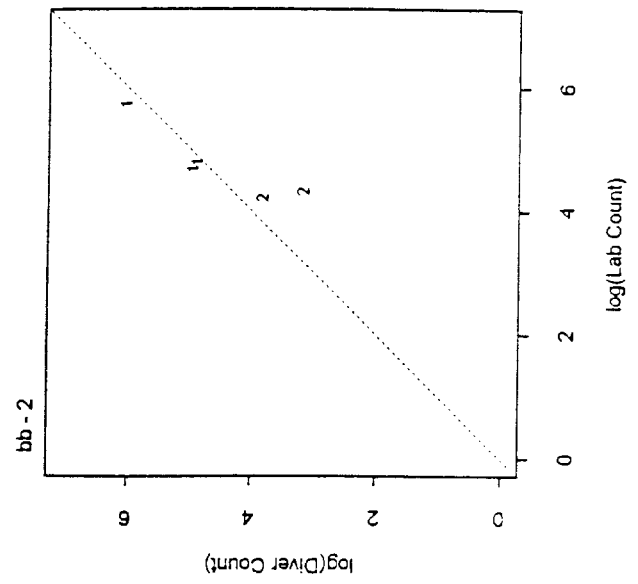


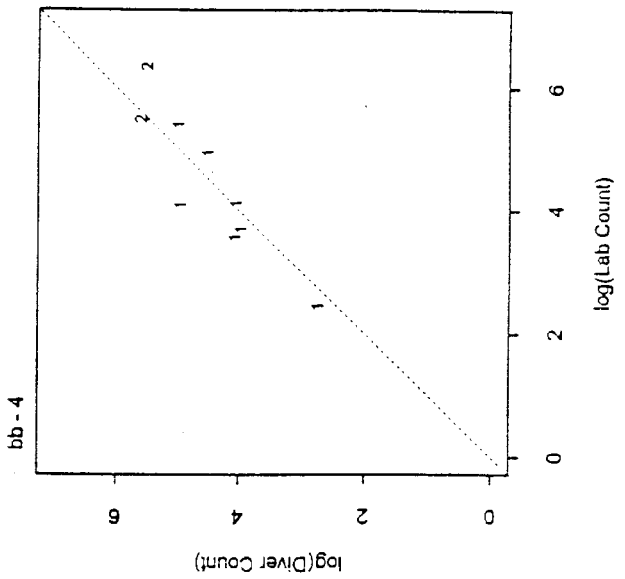


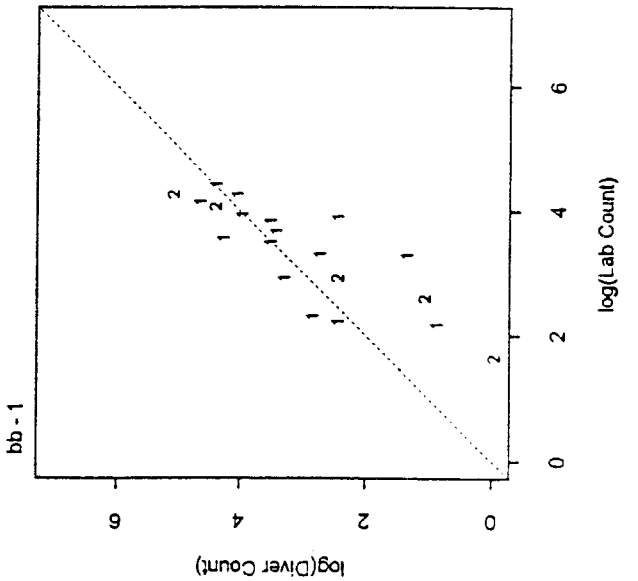


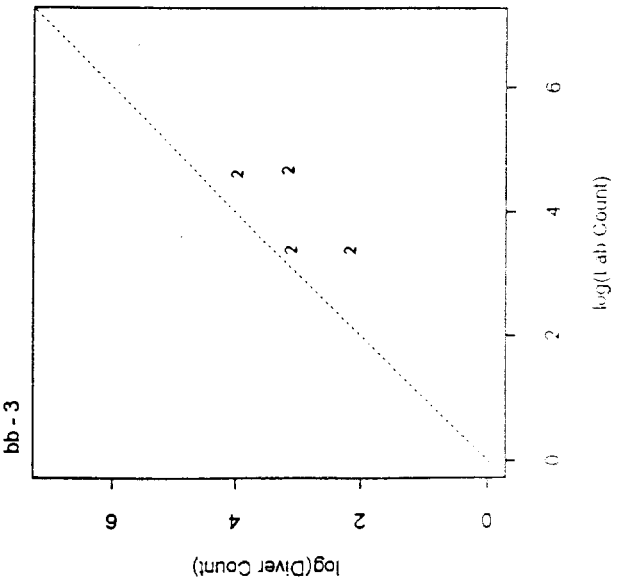
Appendix 2: continued

Year 1990 – Diver bb



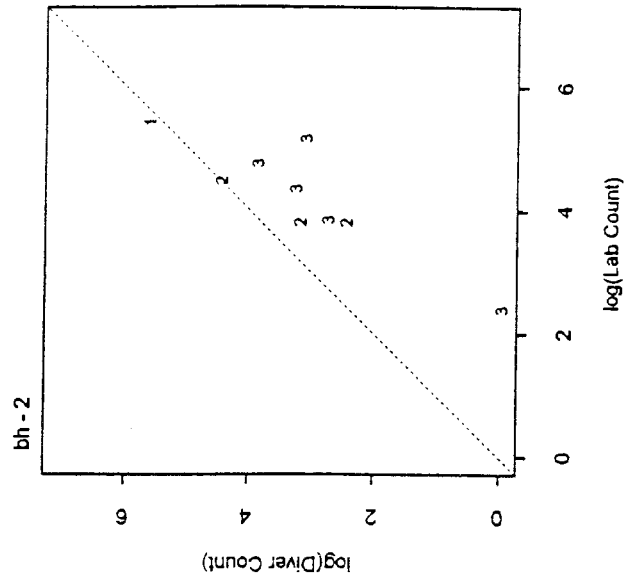


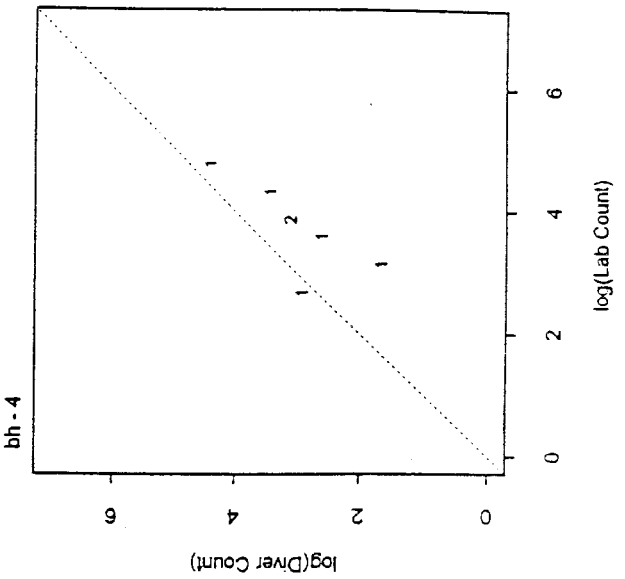


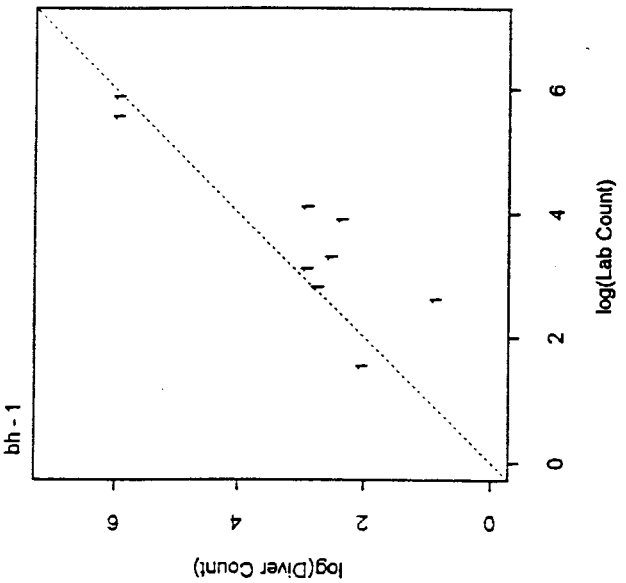


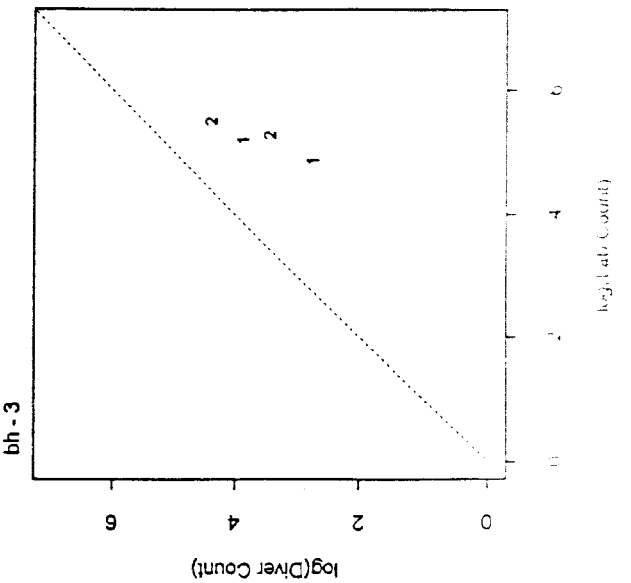
Appendix 2: continued

Year 1995 – Diver bh



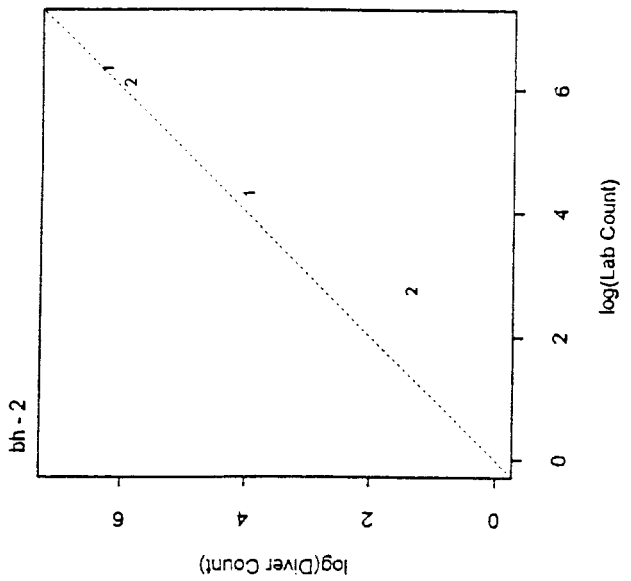


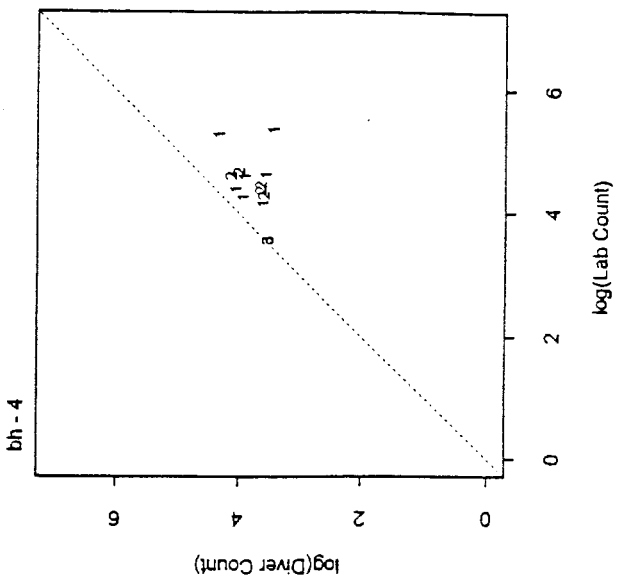


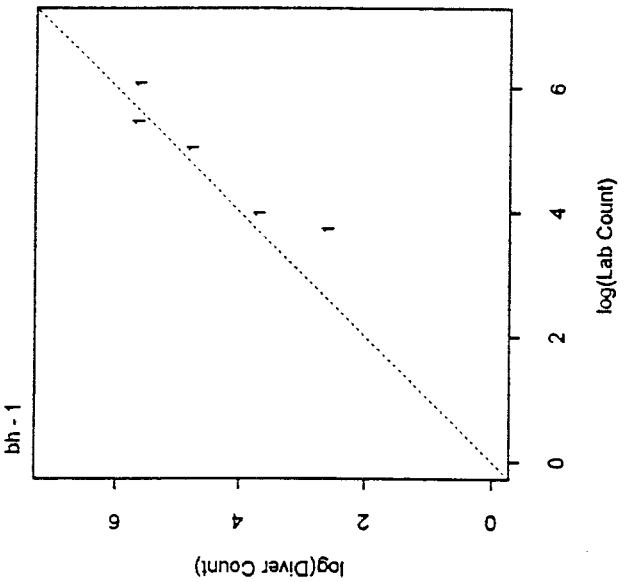


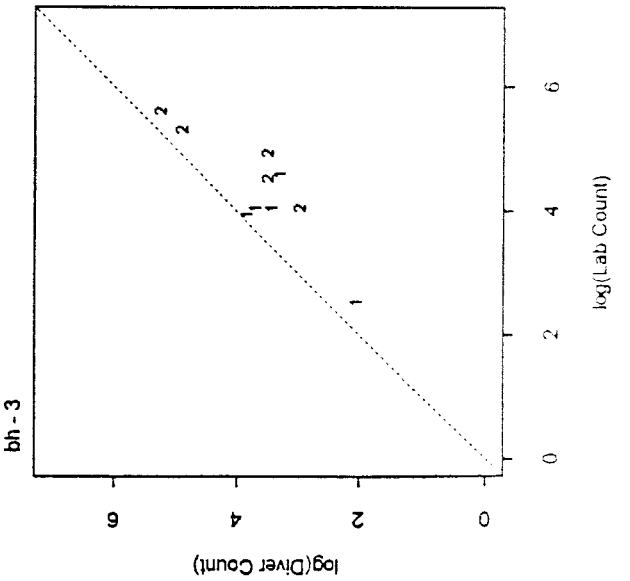
Appendix 2: continued

Year 1994 – Diver bh



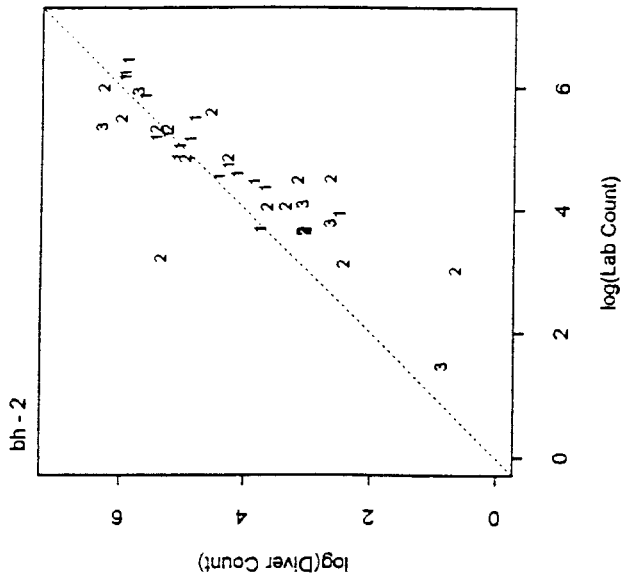


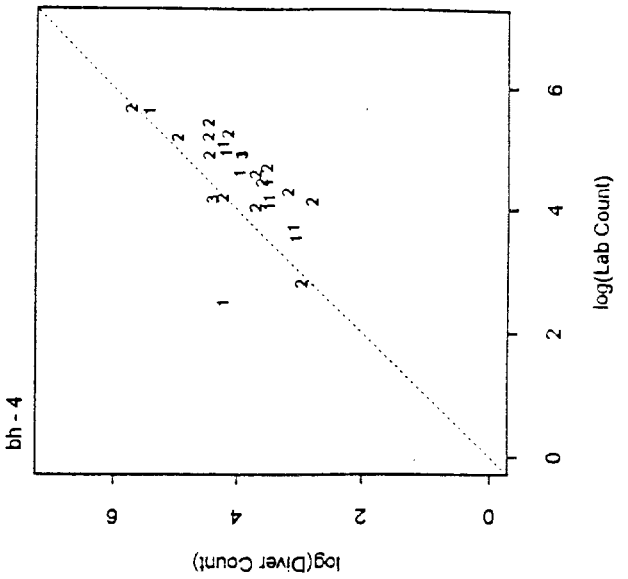


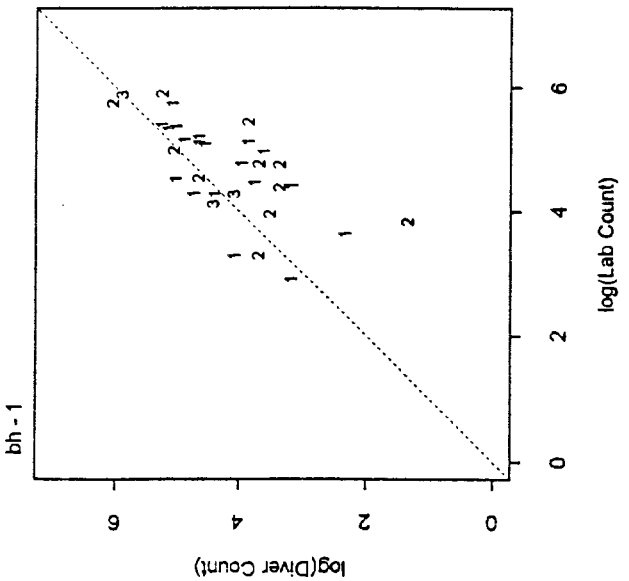


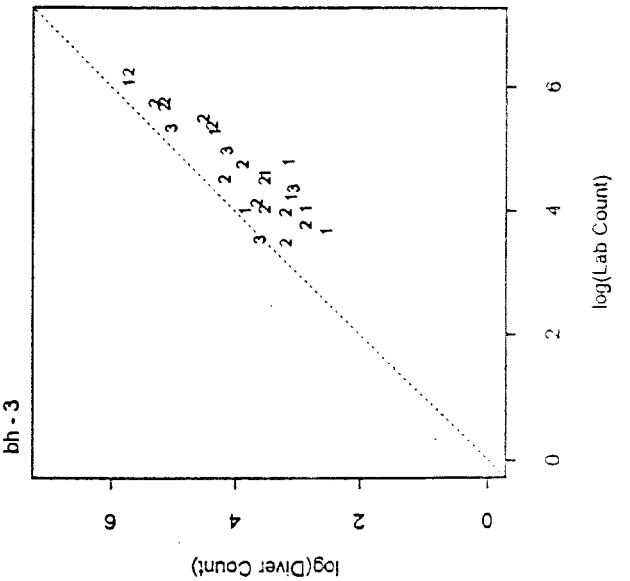
Appendix 2: continued

Year 1992 – Diver bh



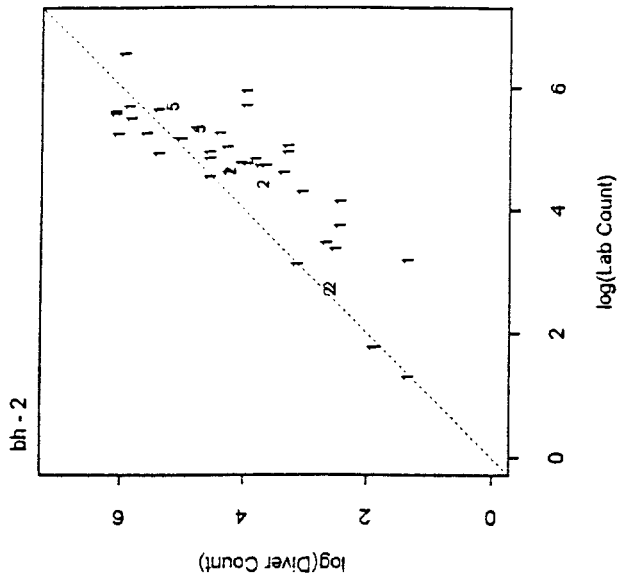


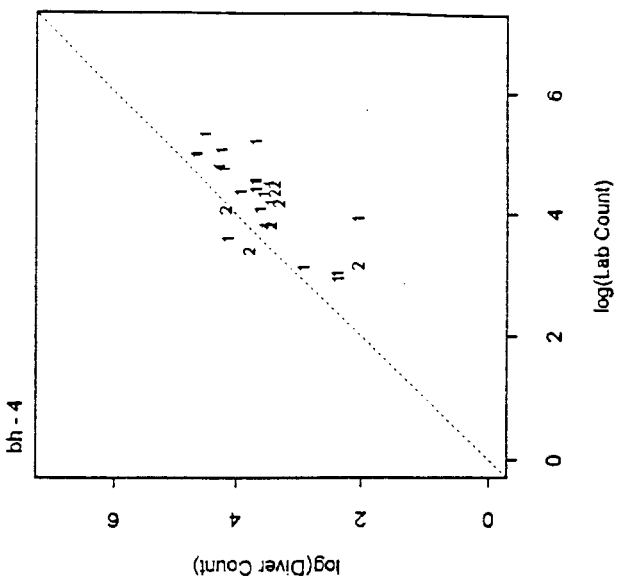


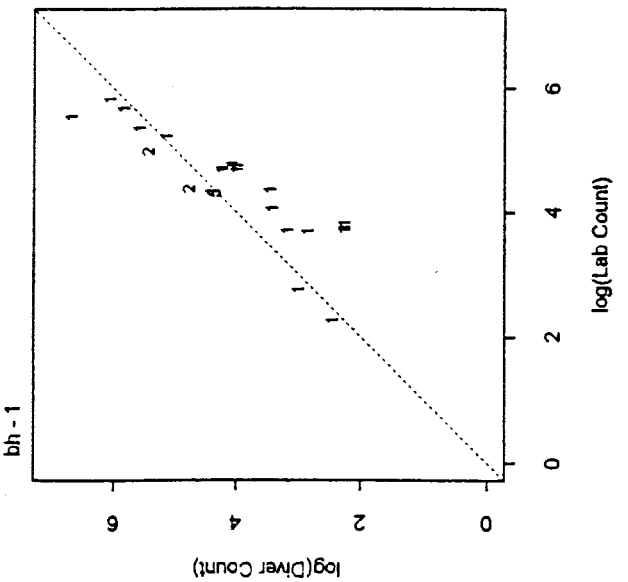


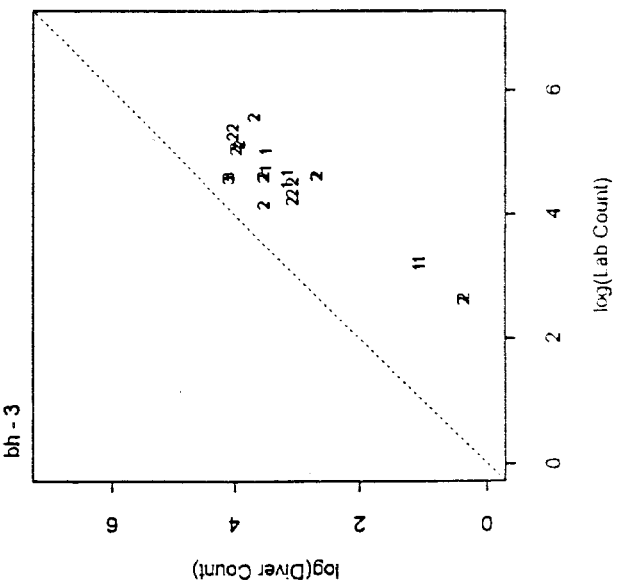
Appendix 2: continued

Year 1991 – Diver bh



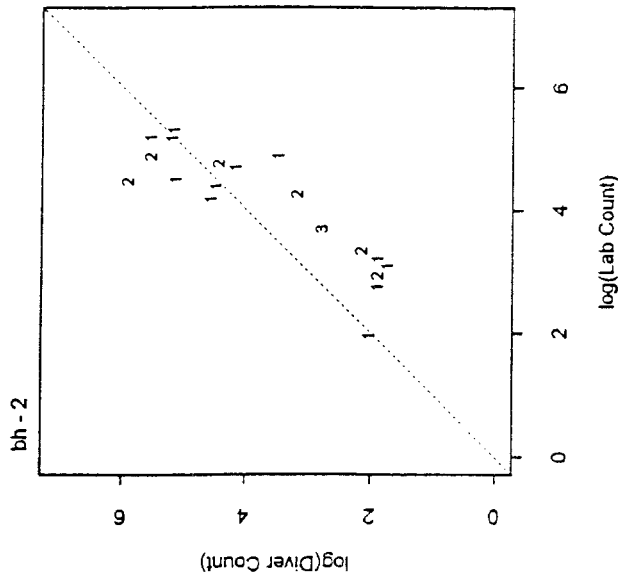


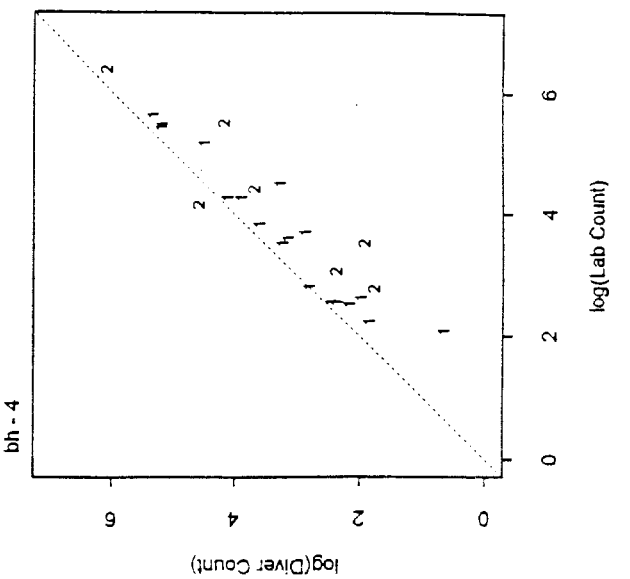


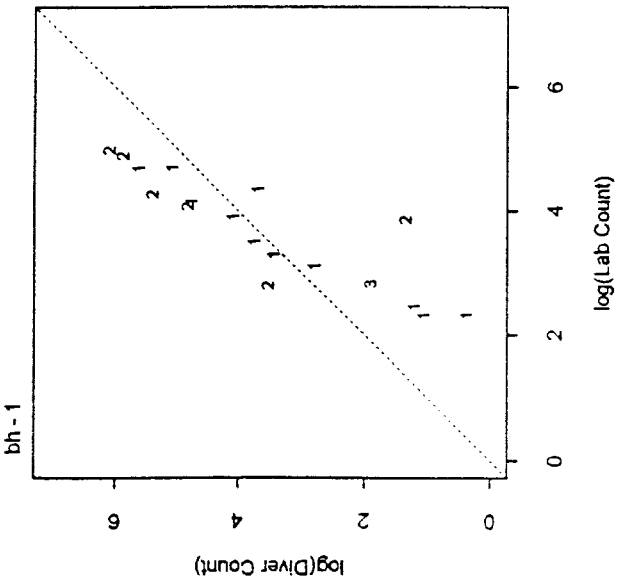


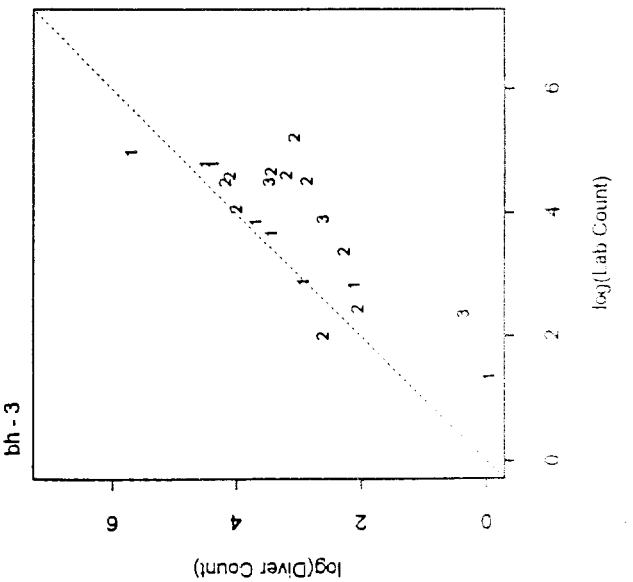
Appendix 2: continued

Year 1990 – Diver bh



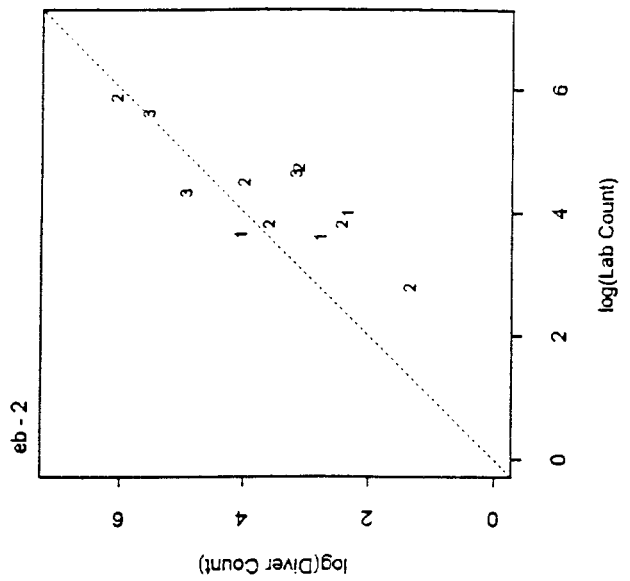


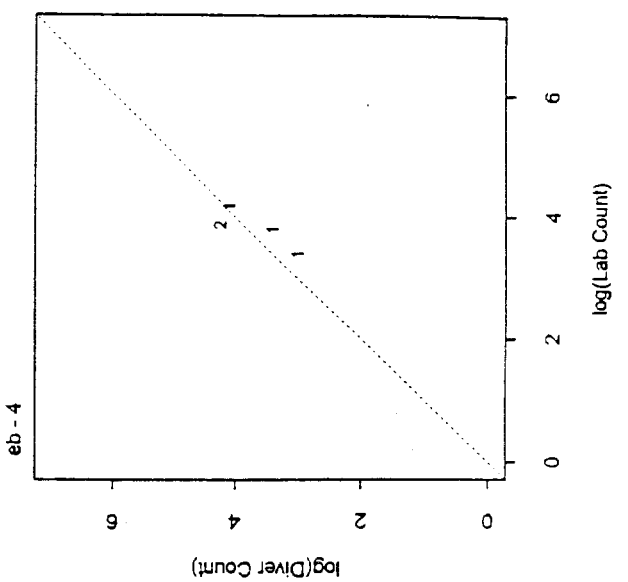


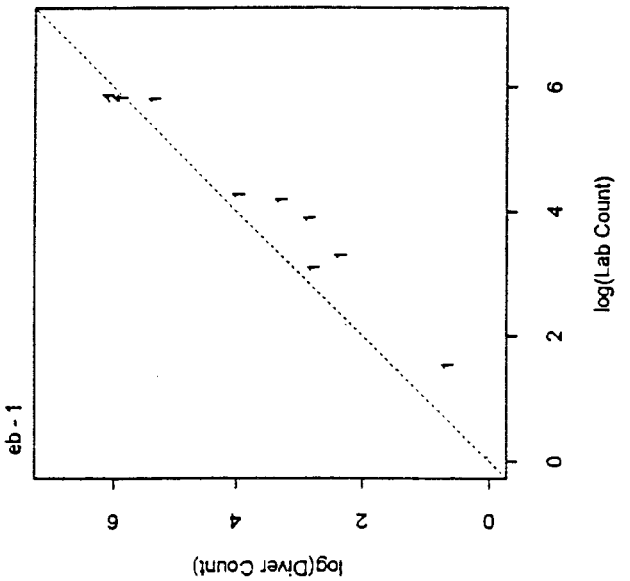


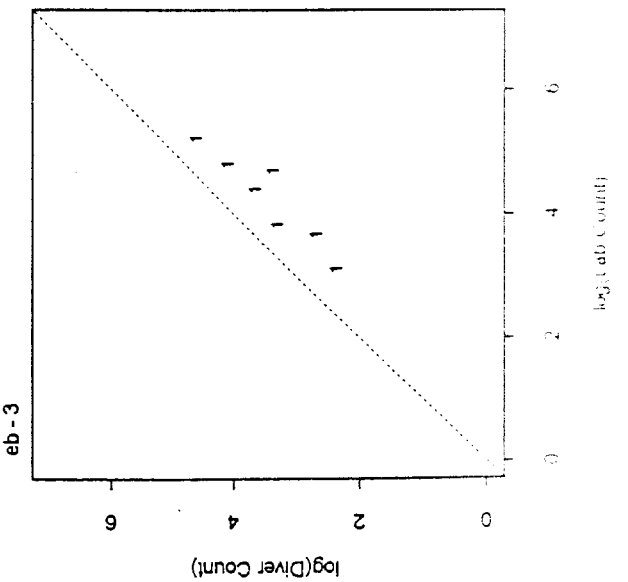
Appendix 2: continued

Year 1995 – Diver eb



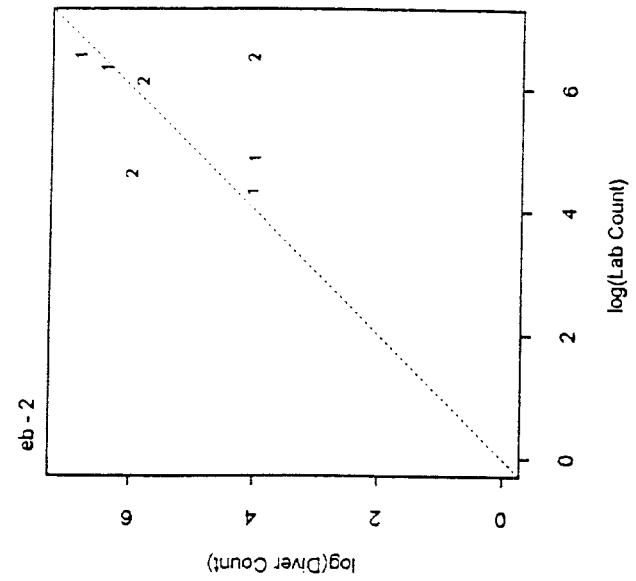


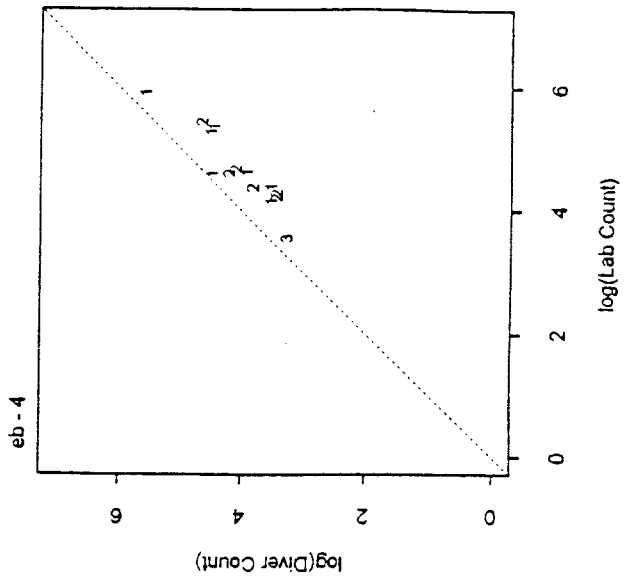


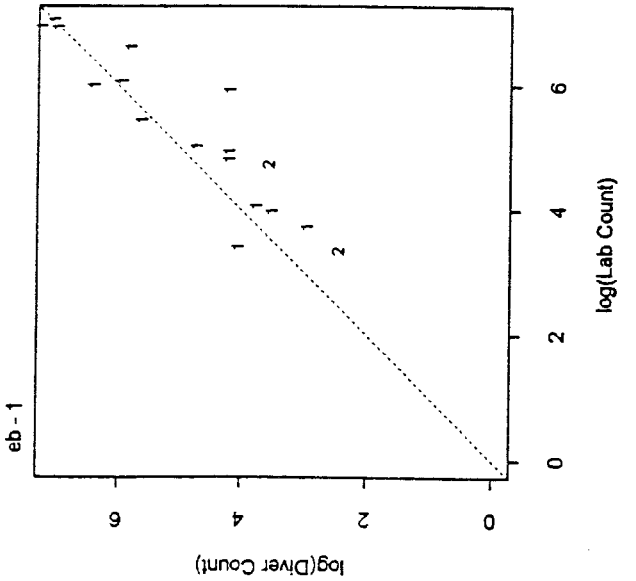


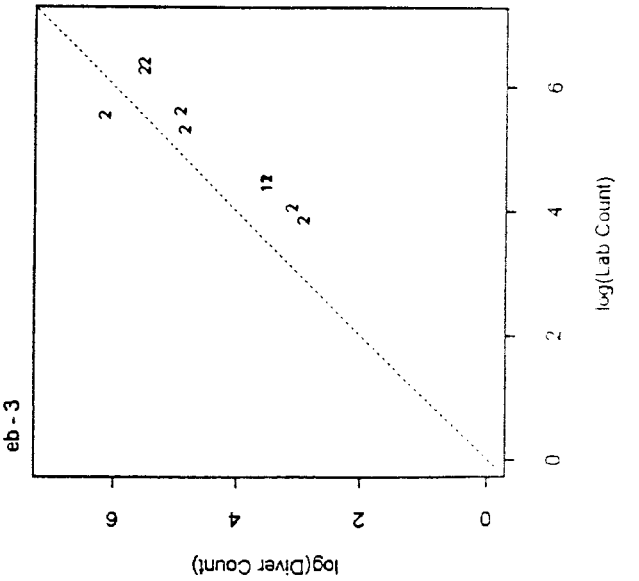
Appendix 2: continued

Year 1994 – Diver eb



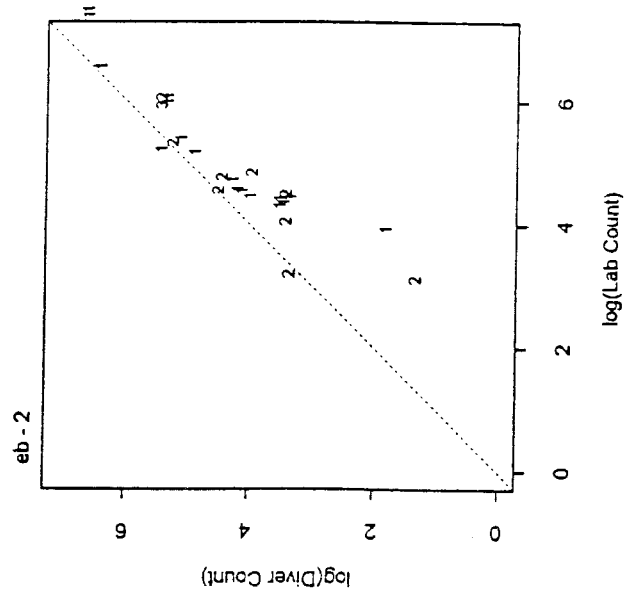


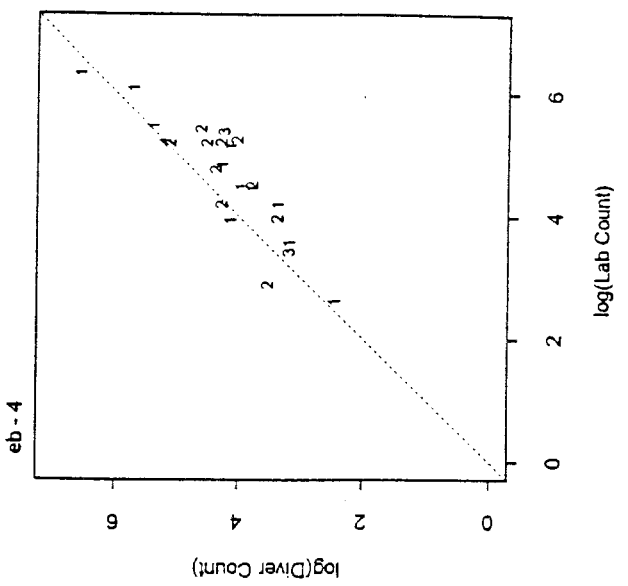


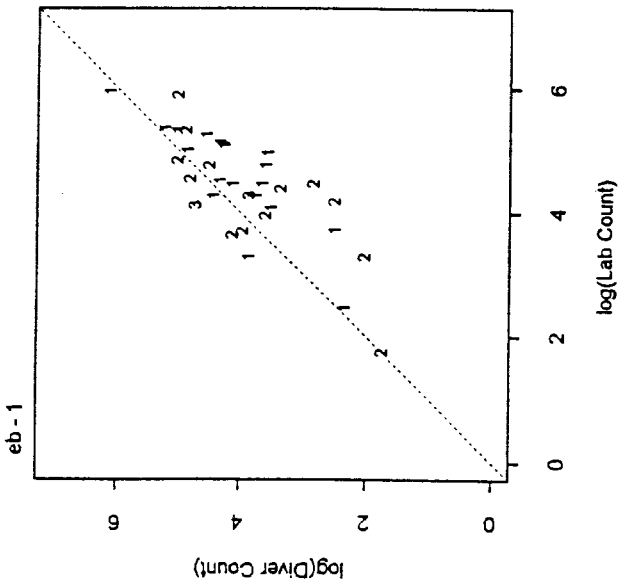


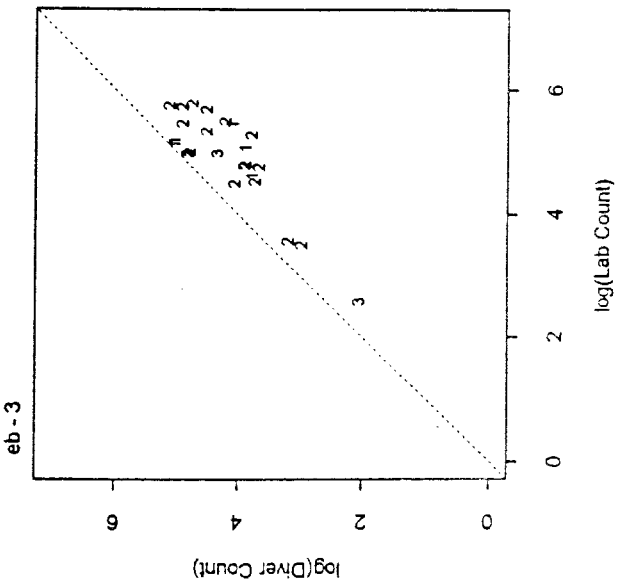
Appendix 2: continued

Year 1992 – Diver eb



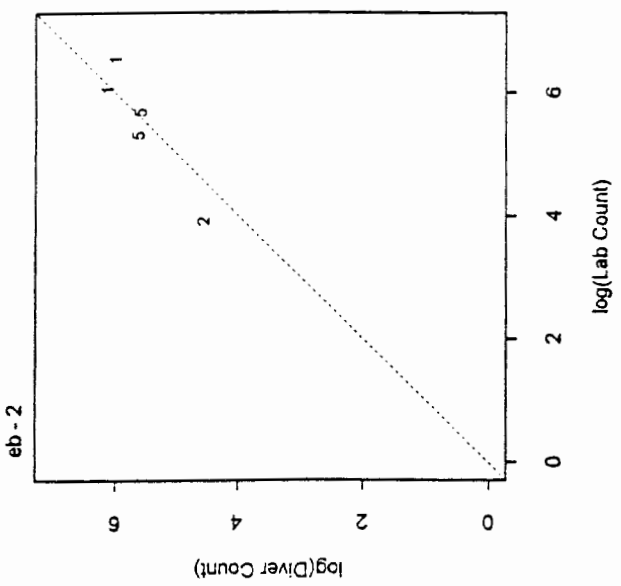


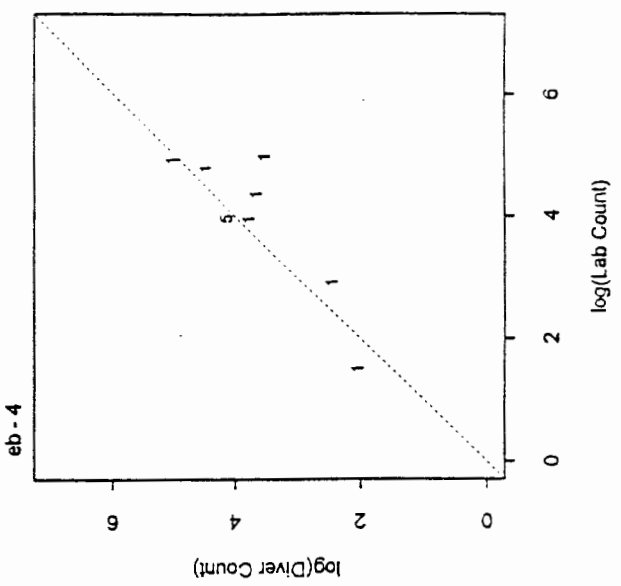


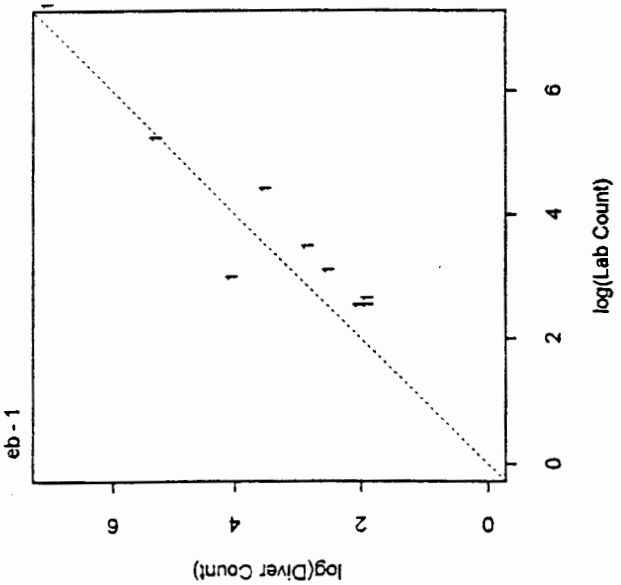


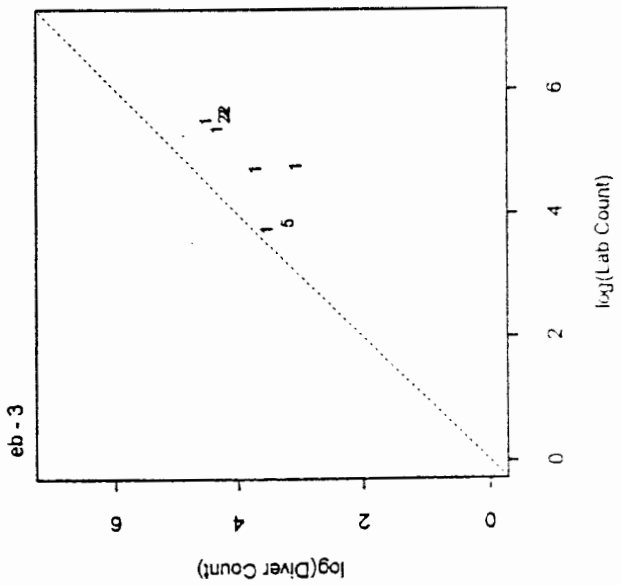
Appendix 2: continued

Year 1991 – Diver eb



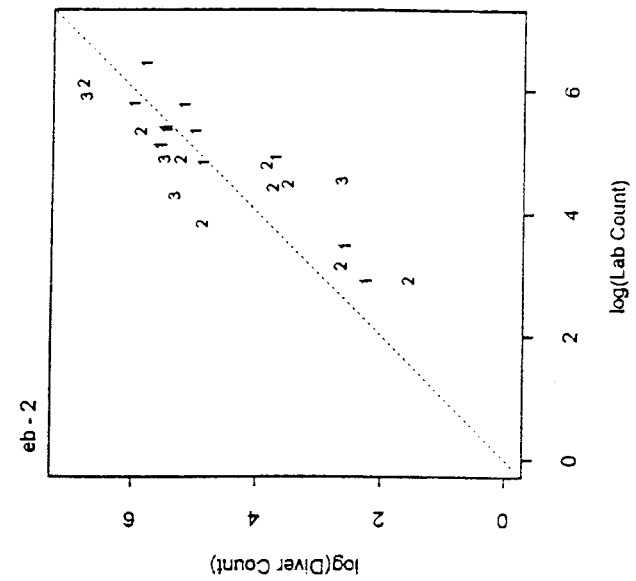


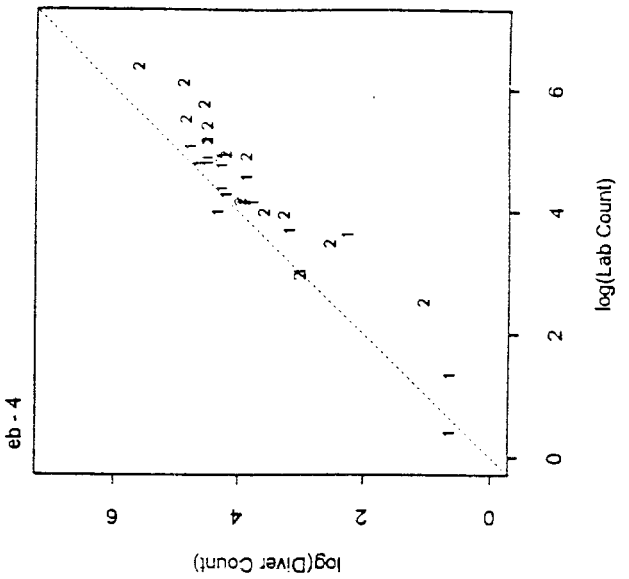


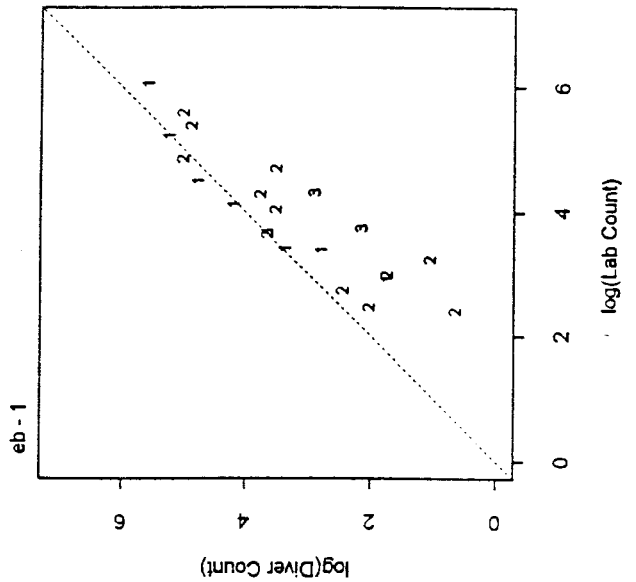


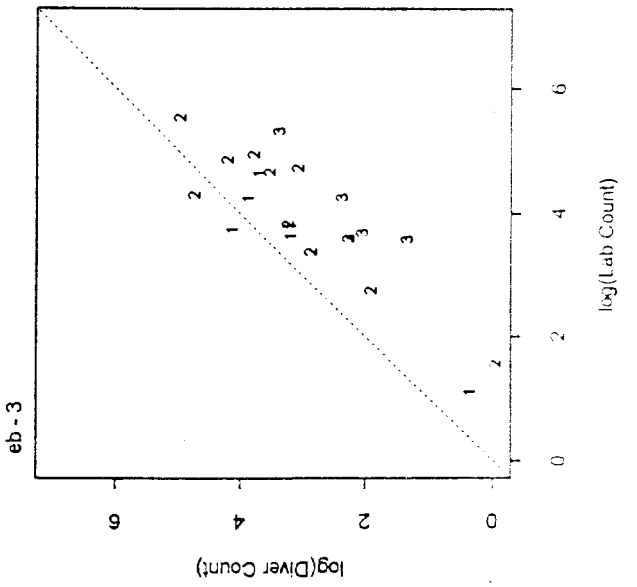
Appendix 2: continued

Year 1990 – Diver eb



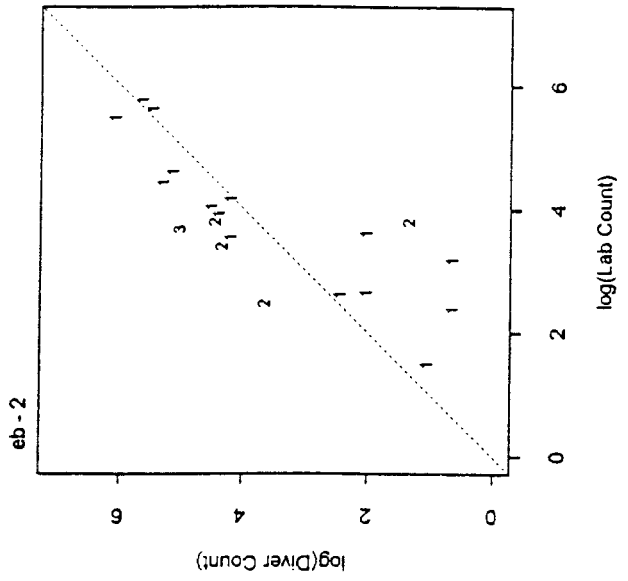


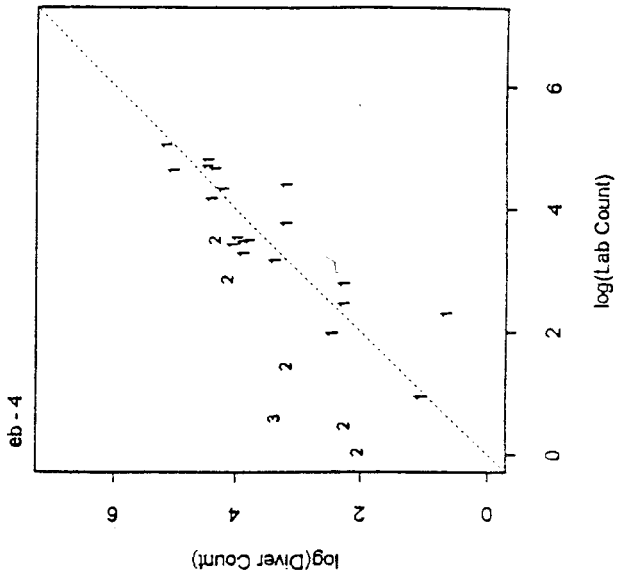


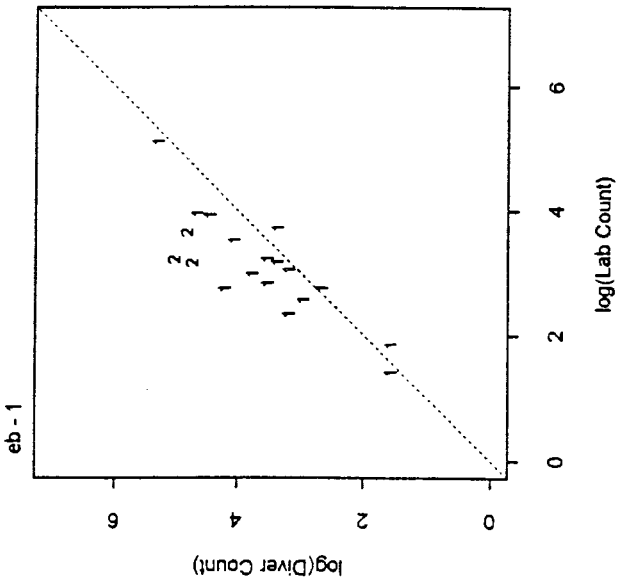


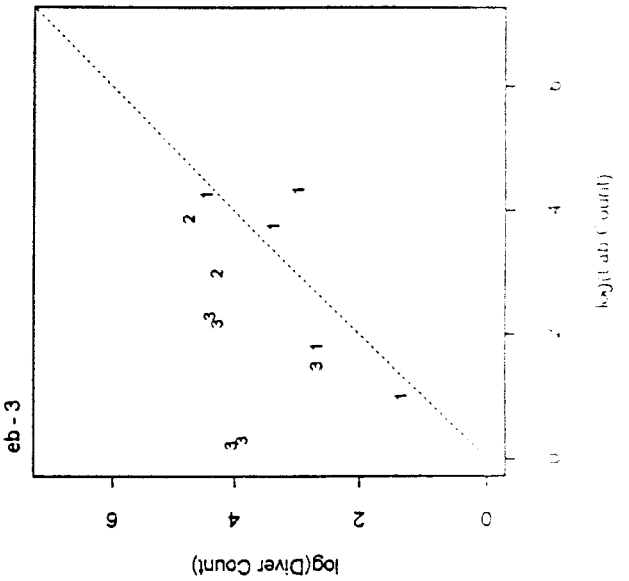
Appendix 2: continued

Year 1989 – Diver eb



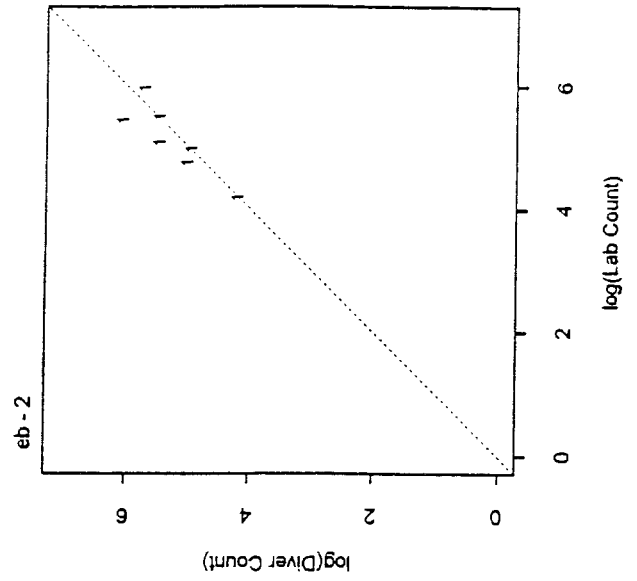


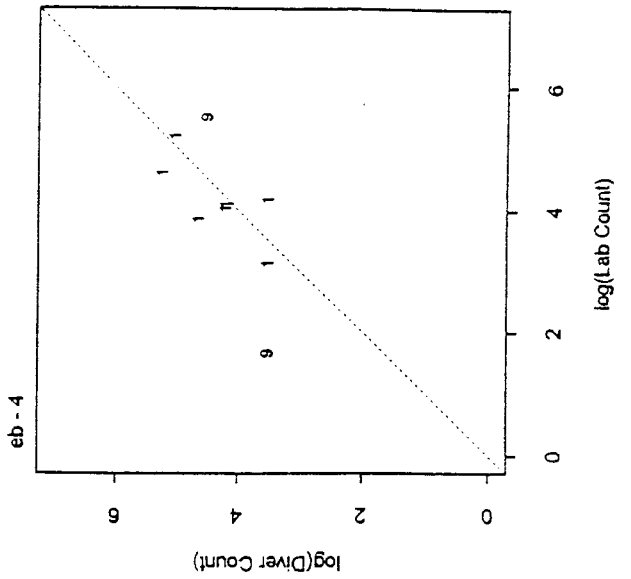


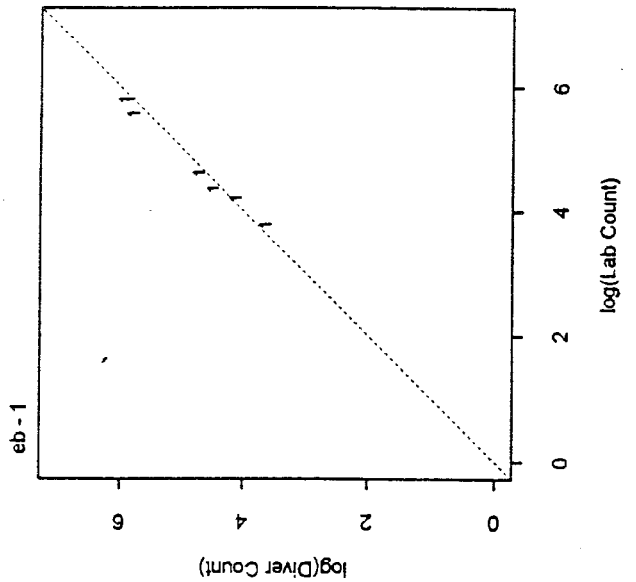


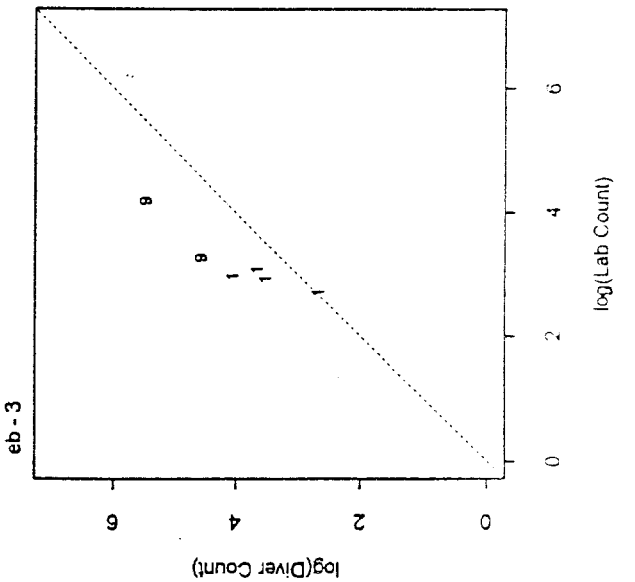
Appendix 2: continued

Year 1988 – Diver eb



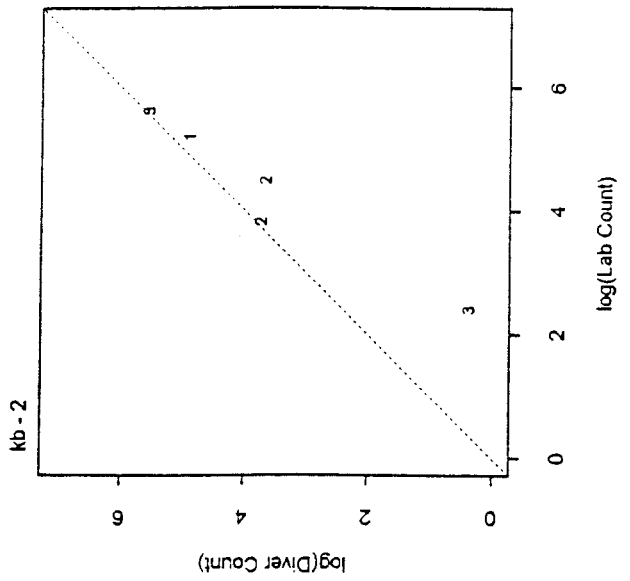


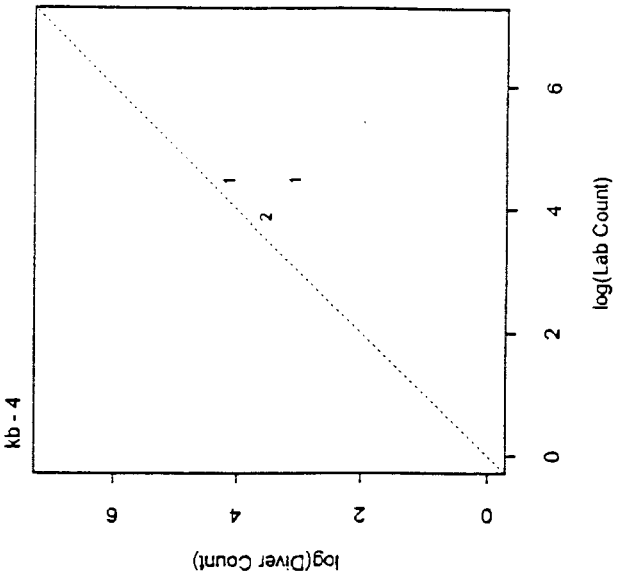


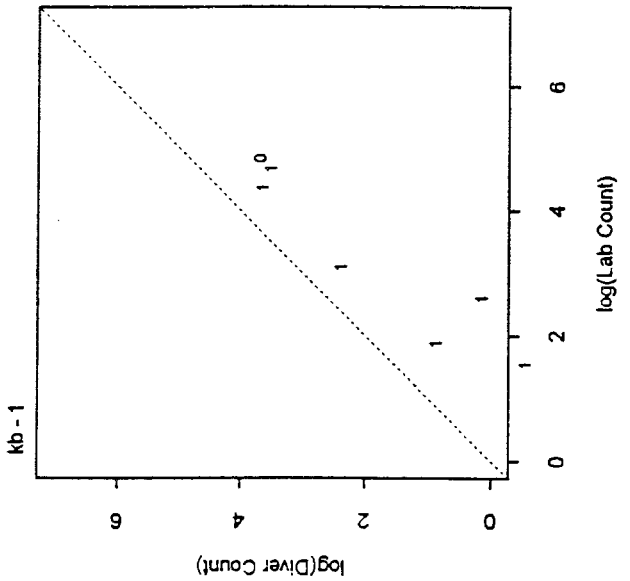


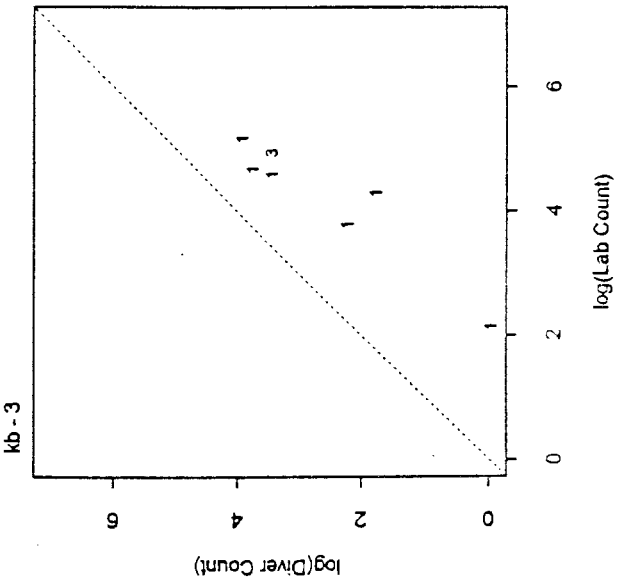
Appendix 2: continued

Year 1995 – Diver kb



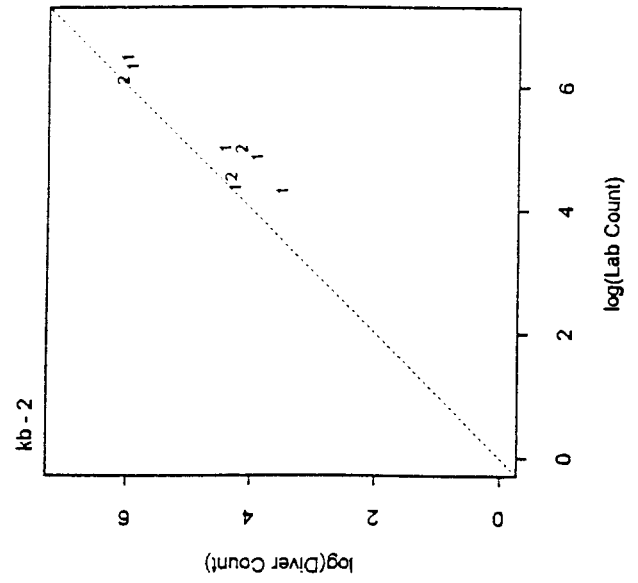


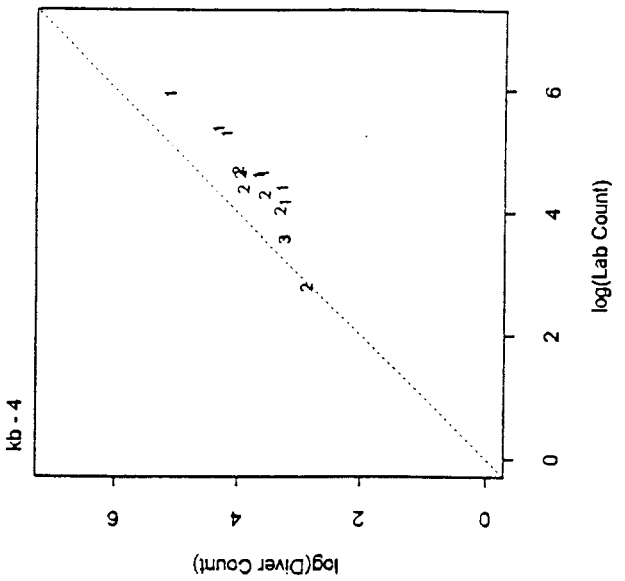


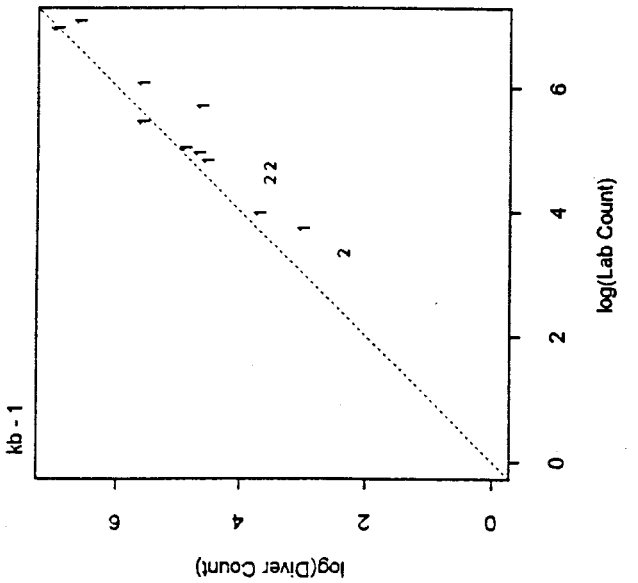


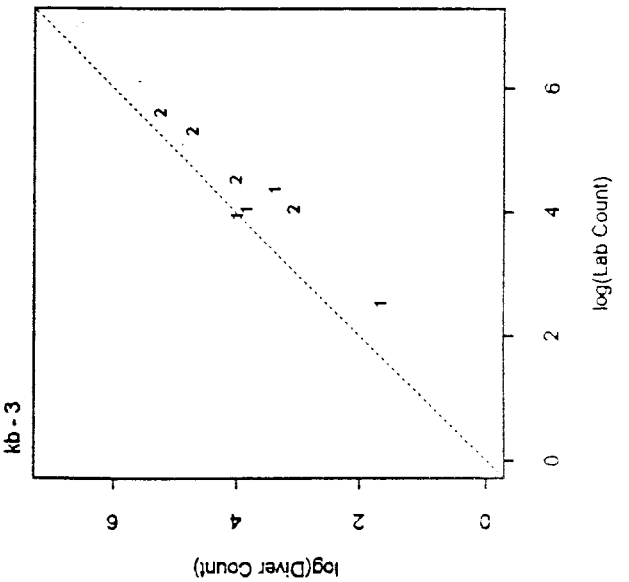
Appendix 2: continued

Year 1994 – Diver kb



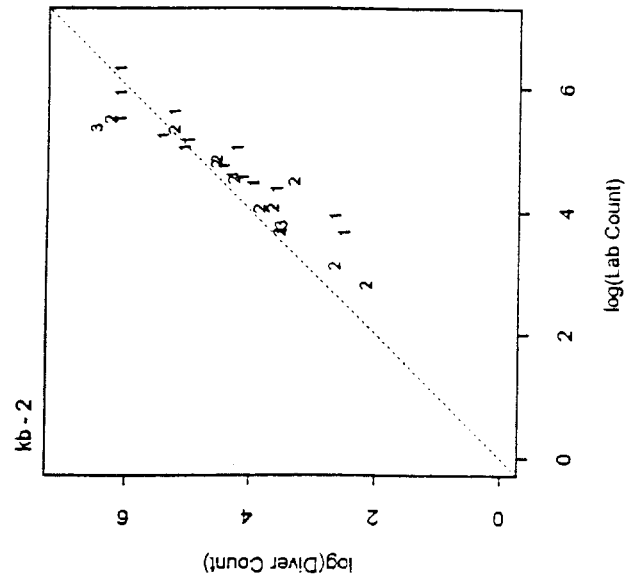


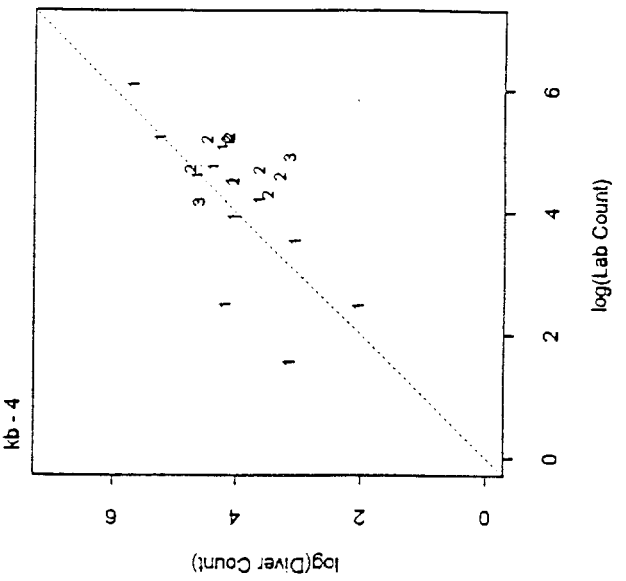


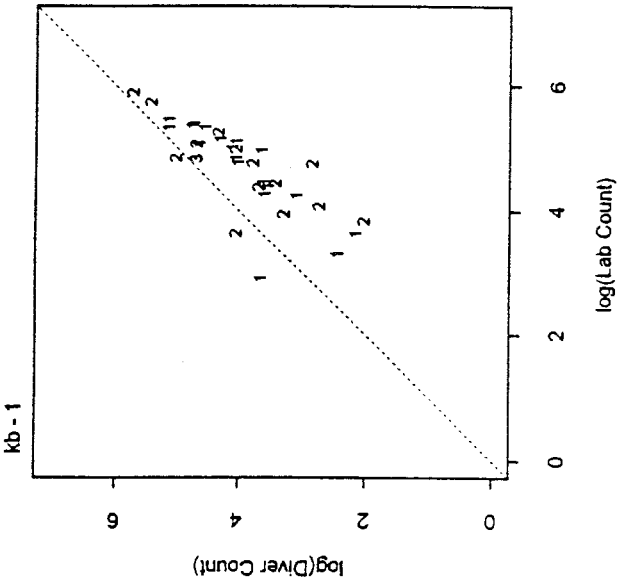


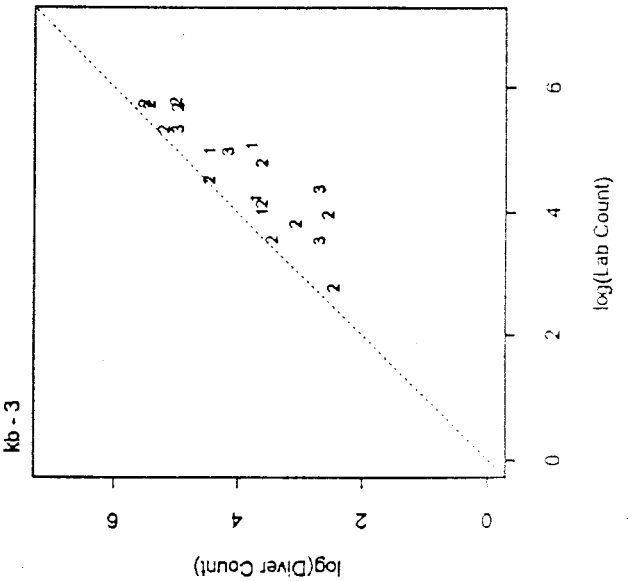
Appendix 2: continued

Year 1992 – Diver kb



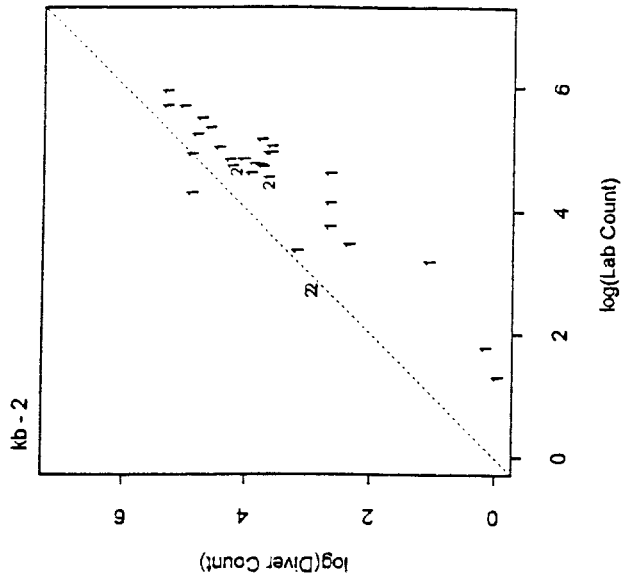


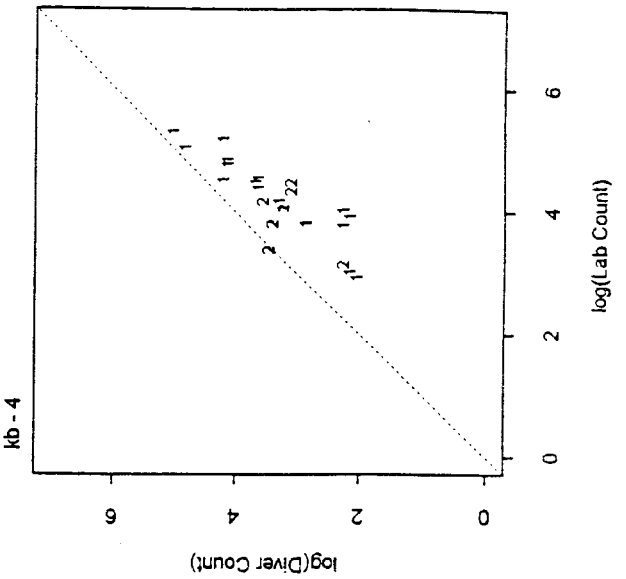


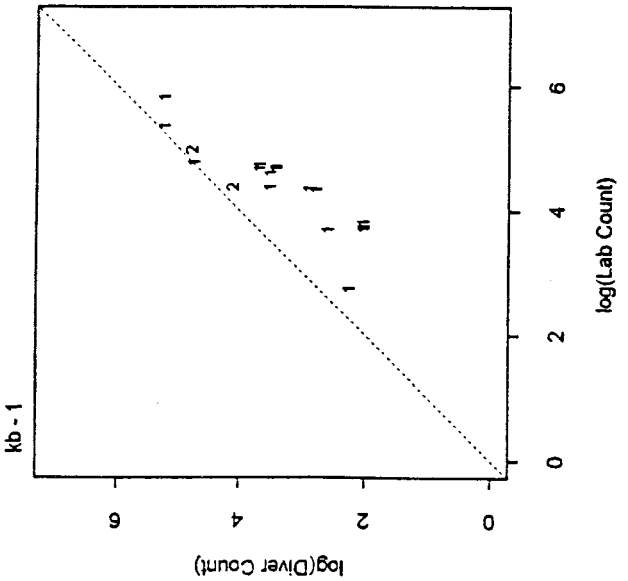


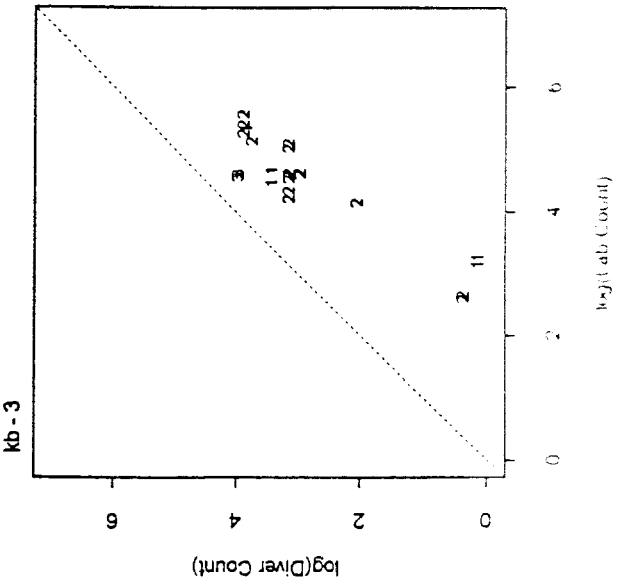
Appendix 2: continued

Year 1991 – Diver kb



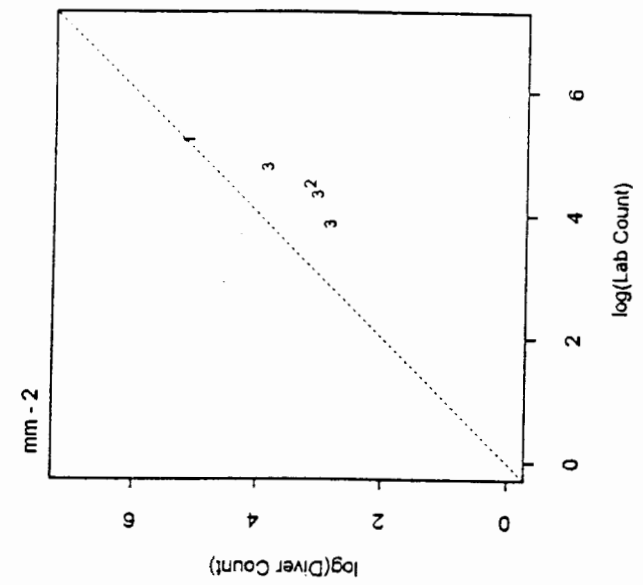


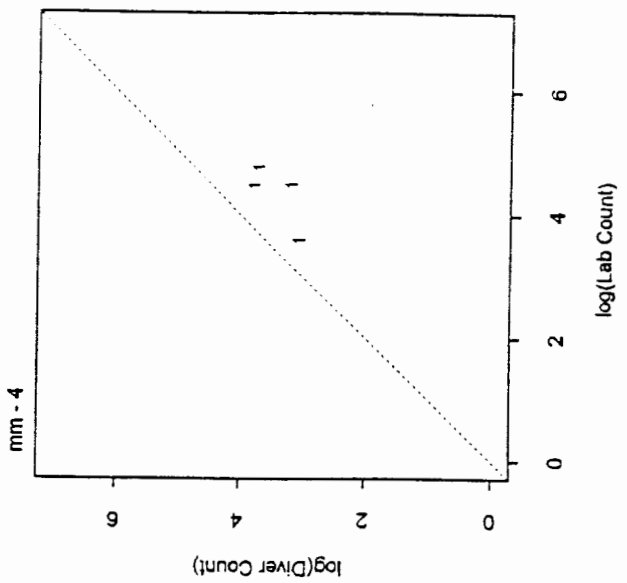


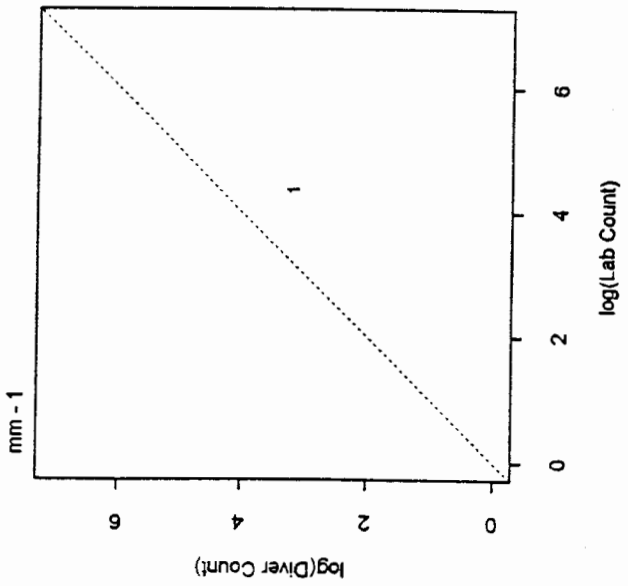


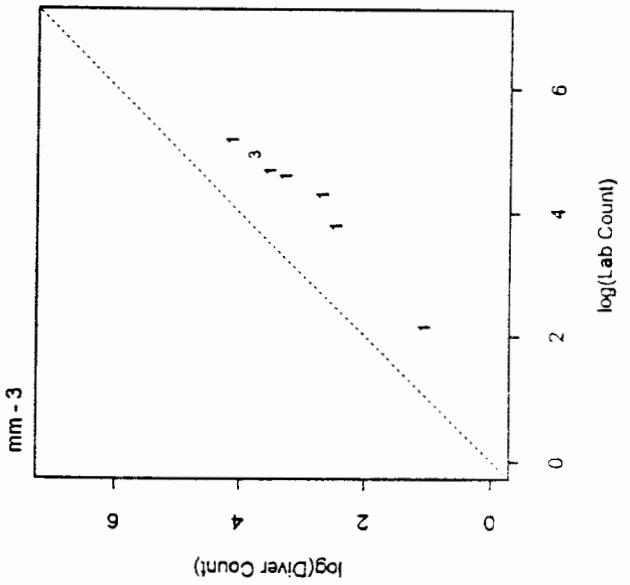
Appendix 2: continued

Year 1995 – Diver mm



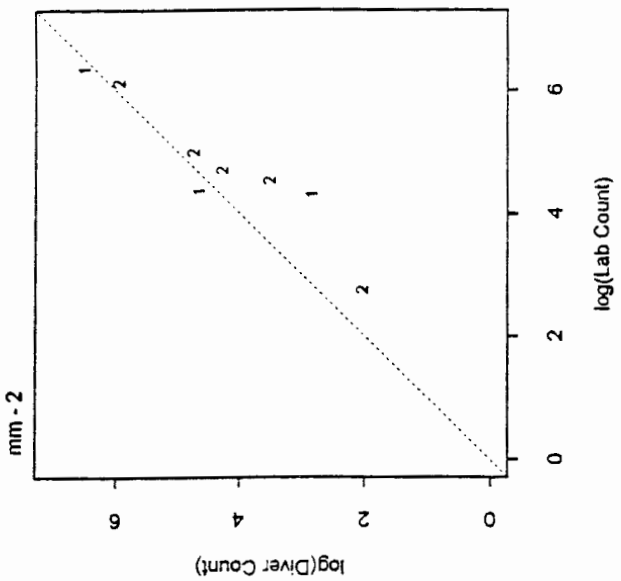


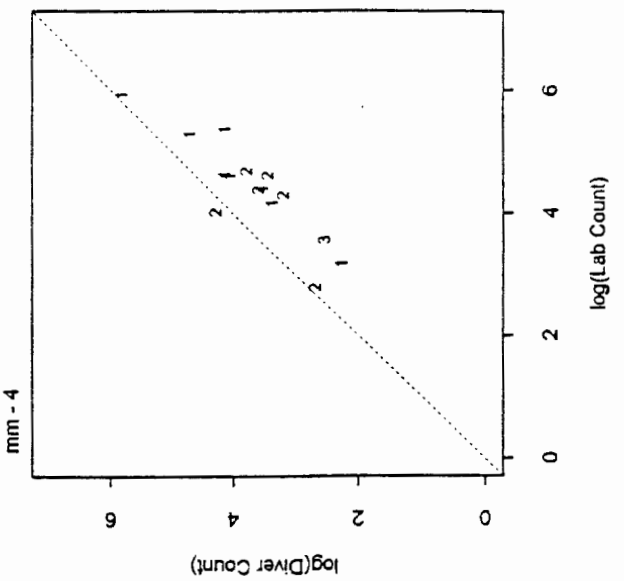


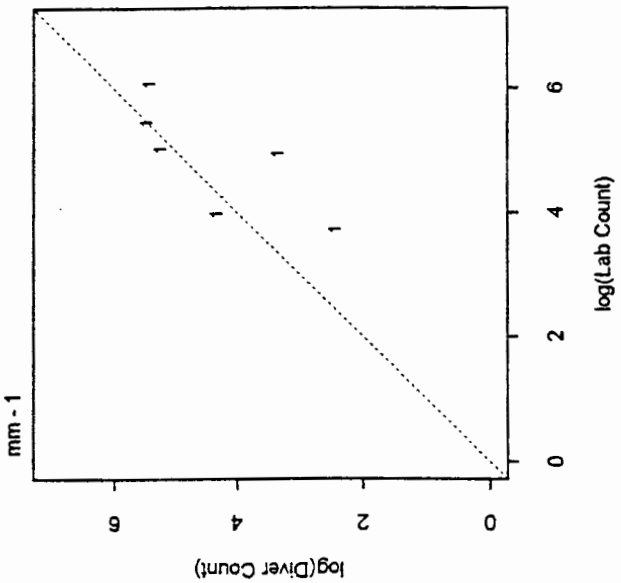


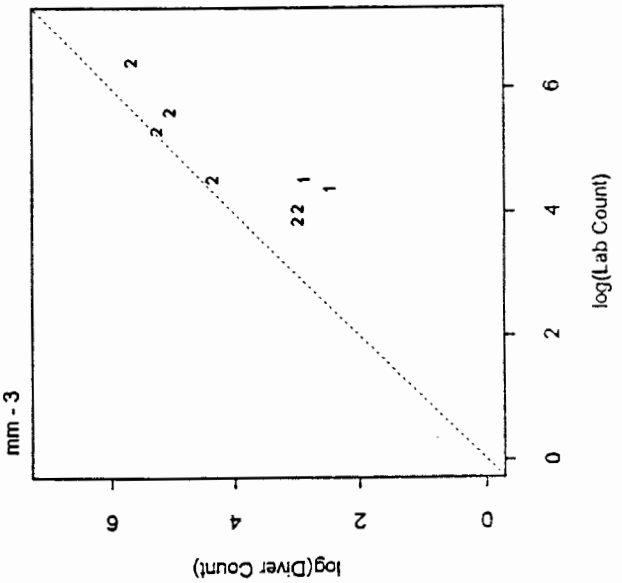
Appendix 2: continued

Year 1994 – Diver mm



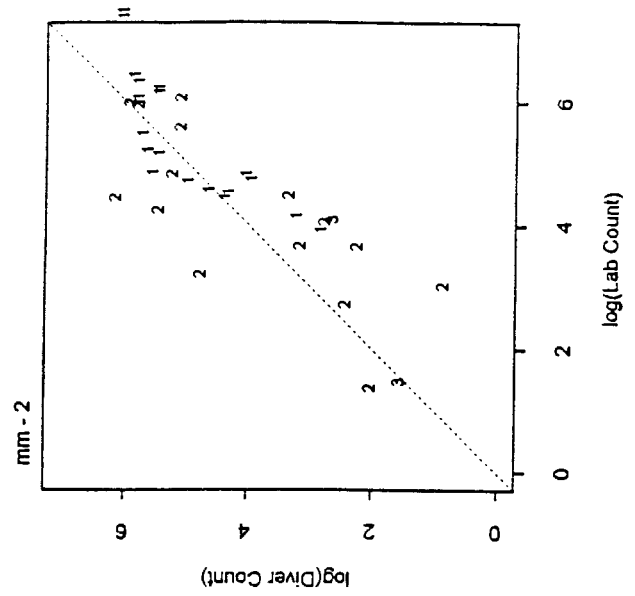


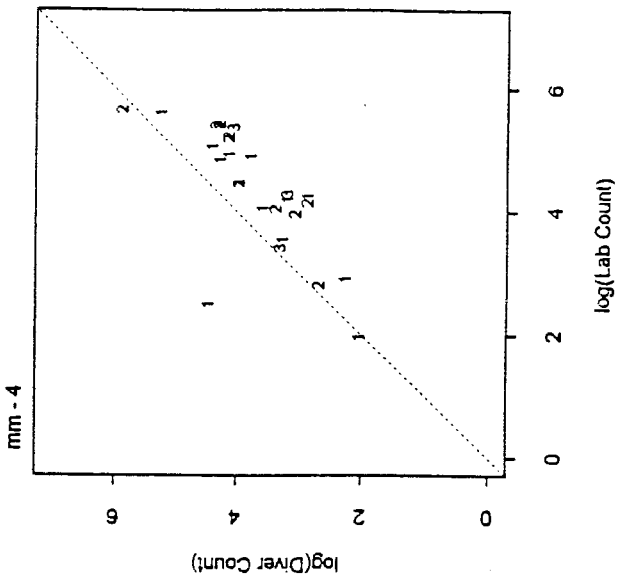


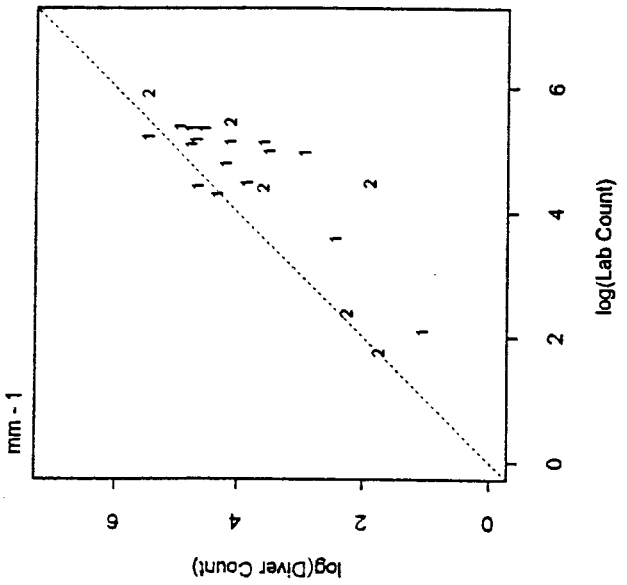


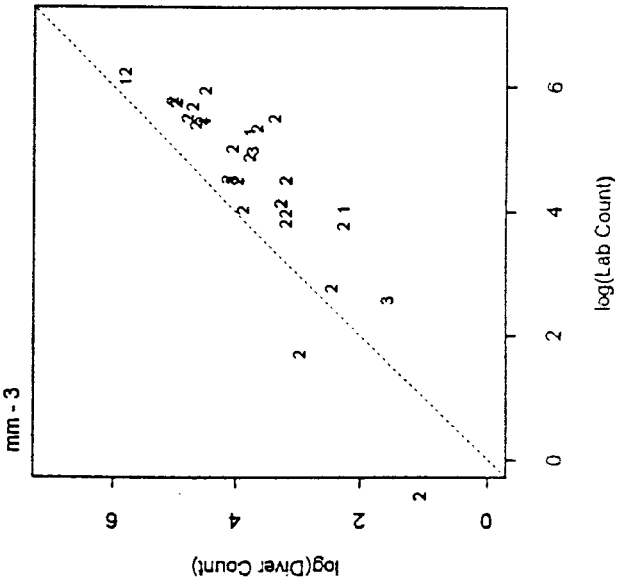
Appendix 2: continued

Year 1992 – Diver mm









Appendix 3: Weighted regression results

```
> fit.bb
Call: lm(formula = log(df$est) ~ -1 + repar(df, I, vy = F), weights = 1/(96 - df$year))
Residuals:
    Min     1Q  Median      3Q     Max
 -1.079 -0.2 0.03442 0.2126 1.407

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
repar(df, I, vy = F)s1   0.9779   0.0062   156.5127   0.0000
repar(df, I, vy = F)s2   0.9819   0.0062   158.1247   0.0000
repar(df, I, vy = F)s3   0.9447   0.0066   143.5101   0.0000
repar(df, I, vy = F)s4   0.9554   0.0068   141.3030   0.0000

Residual standard error: 0.3719 on 308 degrees of freedom
Multiple R-Squared: 0.9966
F-statistic: 22520 on 4 and 308 degrees of freedom, the p-value is 0
```

```
> fit.bh
Call: lm(formula = log(df$est) ~ -1 + repar(df, I, vy = F), weights = 1/(96 - df$year))
Residuals:
    Min      1Q  Median      3Q   Max
 -1.951 -0.1672 0.03479 0.2636 1.334

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
repar(df, I, vy = F)s1   0.9704   0.0065   148.7689   0.0000
repar(df, I, vy = F)s2   0.9530   0.0059   160.8673   0.0000
repar(df, I, vy = F)s3   0.9112   0.0067   135.8535   0.0000
repar(df, I, vy = F)s4   0.9462   0.0064   148.8917   0.0000

Residual standard error: 0.3835 on 385 degrees of freedom
Multiple R-Squared: 0.9957
F-statistic: 22160 on 4 and 385 degrees of freedom, the p-value is 0
```

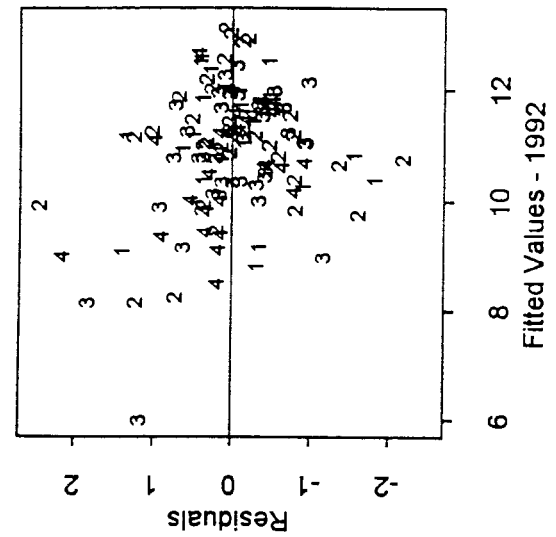
```
> fit.eb
Call: lm(formula = log(df$est) ~ -1 + repar(df, I, vy = F), weights = 1/(96 - df$year))
Residuals:
    Min      1Q  Median      3Q   Max
 -1.377 -0.1926 0.02275 0.2481 2.083

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
repar(df, I, vy = F)s1   0.9742   0.0058   168.2514   0.0000
repar(df, I, vy = F)s2   0.9678   0.0061   158.3826   0.0000
repar(df, I, vy = F)s3   0.9456   0.0067   140.3626   0.0000
repar(df, I, vy = F)s4   0.9728   0.0066   147.4523   0.0000

Residual standard error: 0.3975 on 429 degrees of freedom
Multiple R-Squared: 0.9955
F-statistic: 23710 on 4 and 429 degrees of freedom, the p-value is 0
```

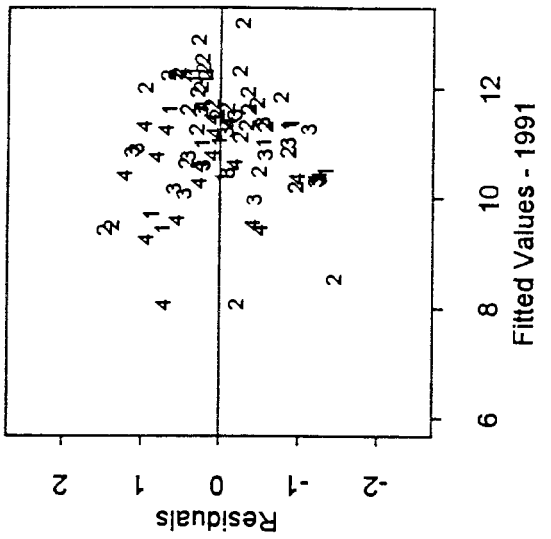
Appendix 3: continued

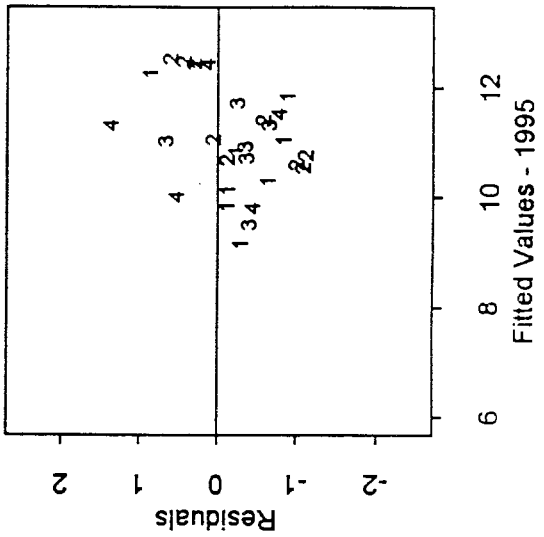
```
> fit.kb
Call: lm(formula = log(df$est) ~ -1 + repar(df, I, vy = F), weights = 1/(96 - df$year))
Residuals:
   Min      1Q   Median     3Q   Max
 -1.79 -0.1813 0.002978 0.2299 1.135

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
repar(df, I, vy = F)s1   0.9340   0.0065   143.1624   0.0000
repar(df, I, vy = F)s2   0.9607   0.0068   142.1444   0.0000
repar(df, I, vy = F)s3   0.9026   0.0074   121.5971   0.0000
repar(df, I, vy = F)s4   0.9435   0.0074   127.2015   0.0000

Residual standard error: 0.3814 on 271 degrees of freedom
Multiple R-Squared: 0.9962
F-statistic: 17920 on 4 and 271 degrees of freedom, the p-value is 0
```

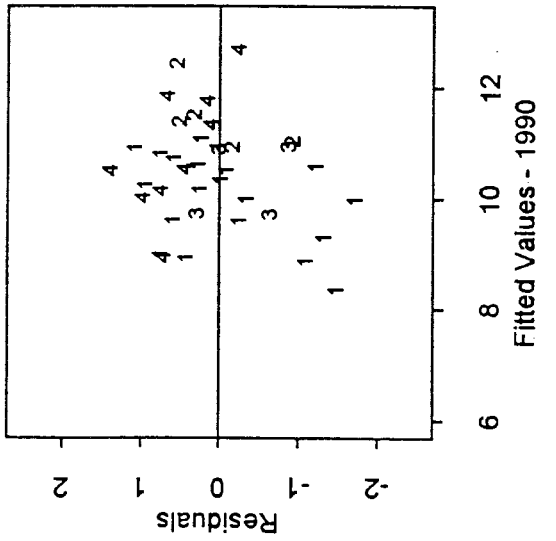
```
> fit.mm
Call: lm(formula = log(df$est) ~ -1 + repar(df, I, vy = F), weights = 1/(96 - df$year))
Residuals:
     Min      1Q  Median    3Q   Max
 -0.9311 -0.2408 0.03588 0.241 1.293

Coefficients:
                          Value Std. Error  t value Pr(>|t|)
repar(df, I, vy = F)s1   0.9431   0.0111    84.9122   0.0000
repar(df, I, vy = F)s2   0.9617   0.0079   121.1885   0.0000
repar(df, I, vy = F)s3   0.9167   0.0079   115.8717   0.0000
repar(df, I, vy = F)s4   0.9397   0.0082   114.5988   0.0000

Residual standard error: 0.3956 on 168 degrees of freedom
Multiple R-Squared: 0.9965
F-statistic: 12110 on 4 and 168 degrees of freedom, the p-value is 0
```

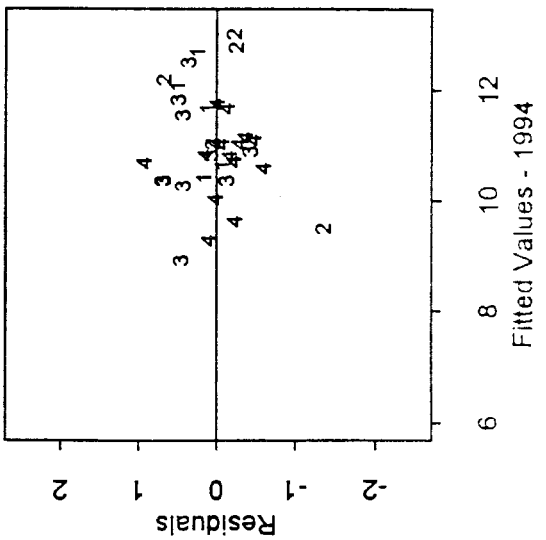
Appendix 3: continued





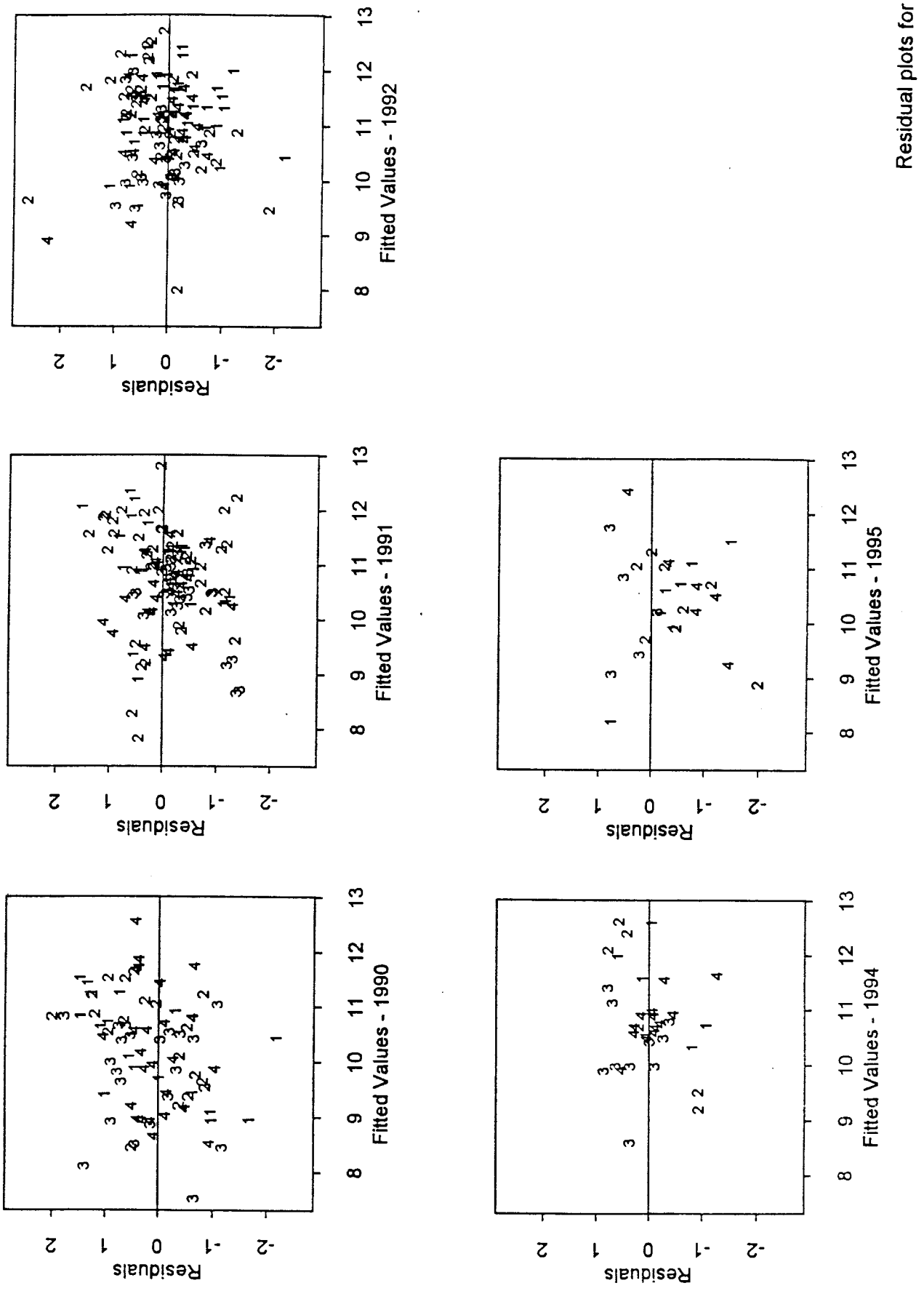




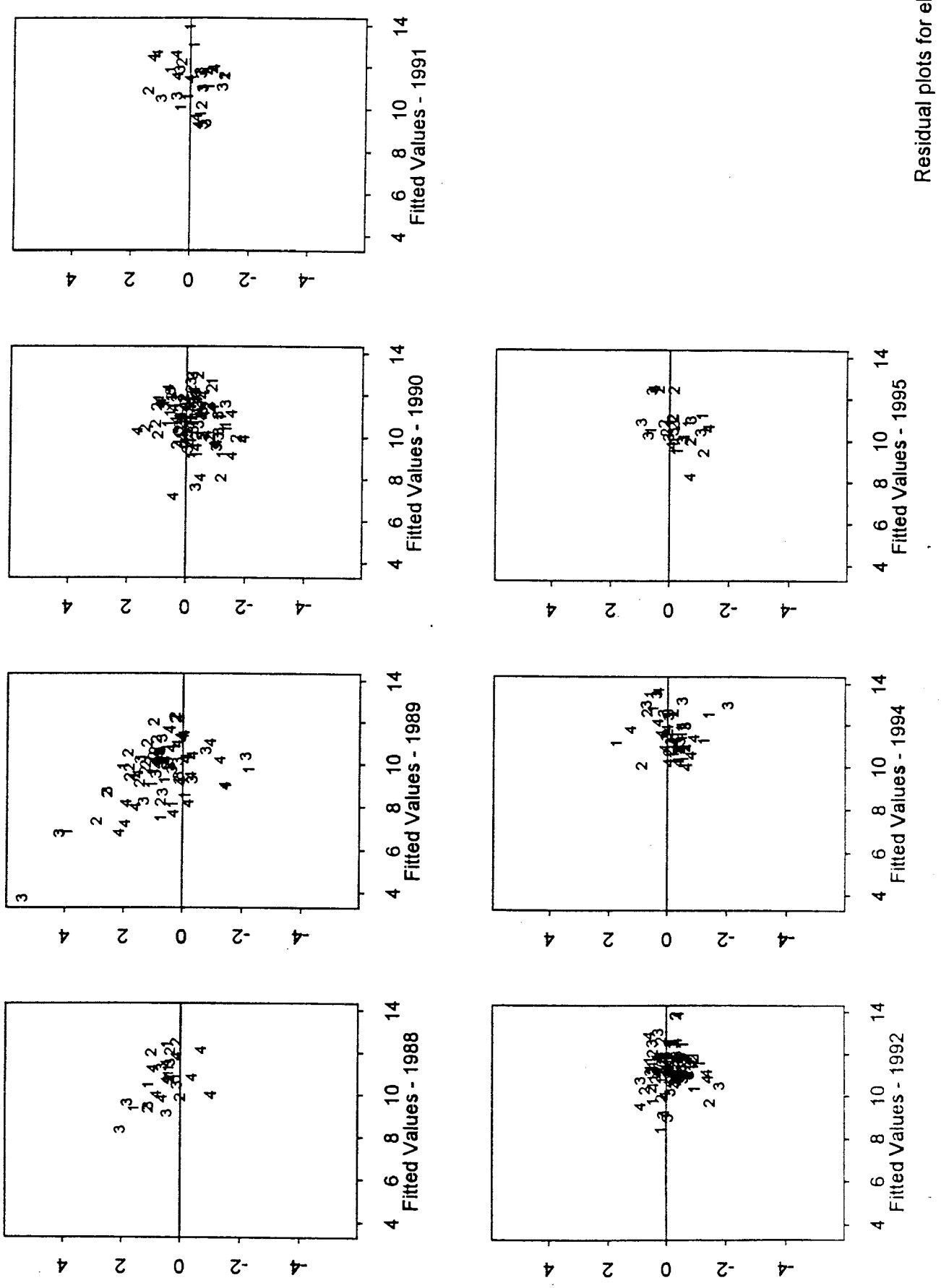


Residual plots for bb

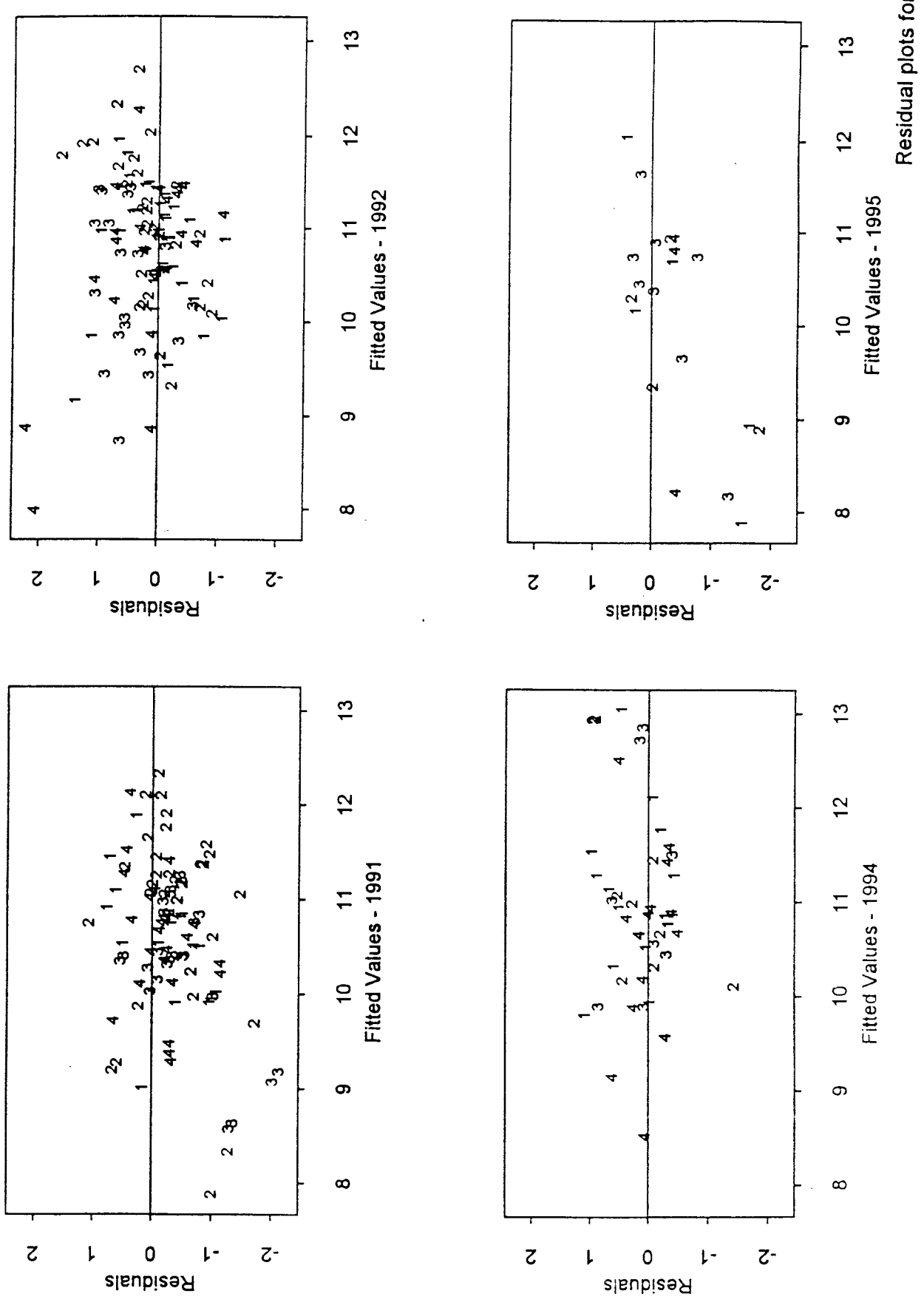
Appendix 3: continued



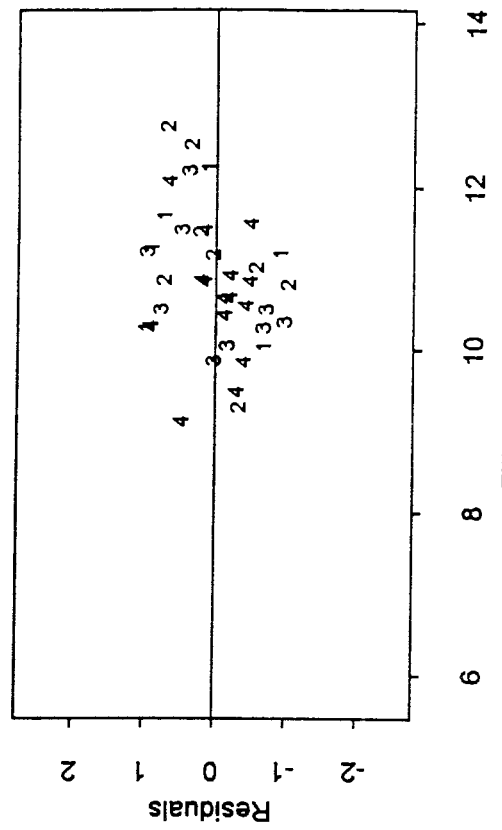
Appendix 3: continued

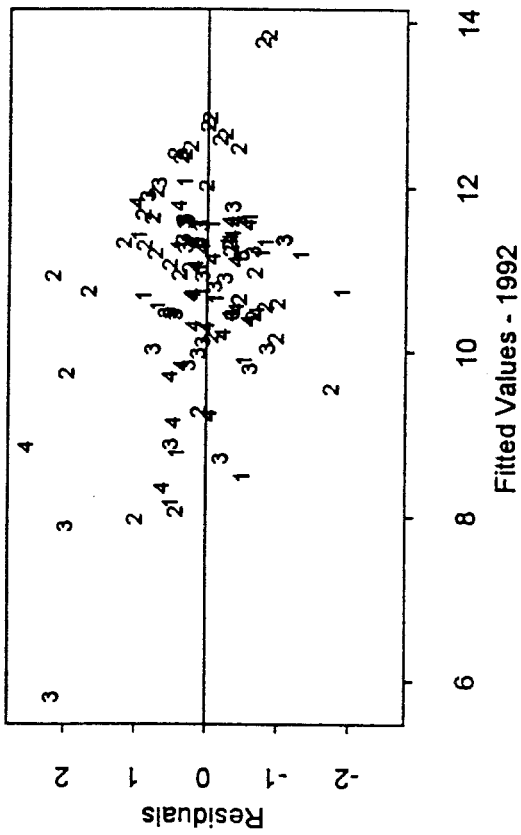


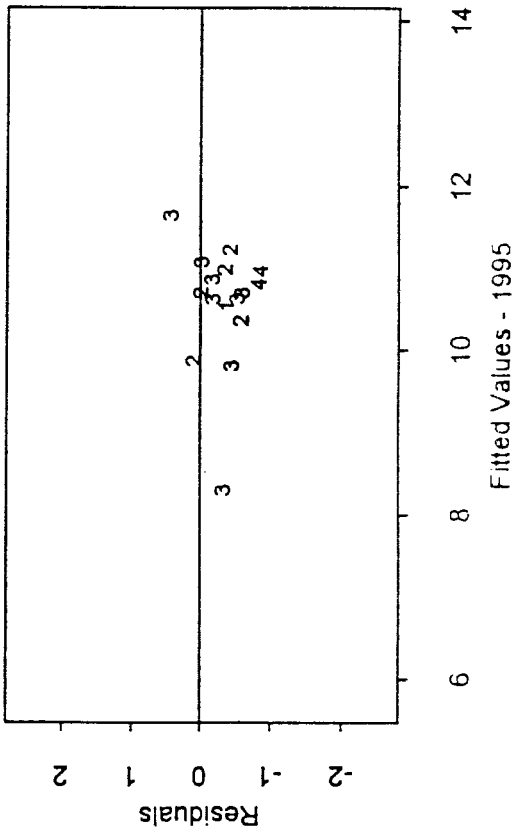
Appendix 3: continued



Appendix 3: continued







Residual plots for mm