AN ANALYSIS OF THE 1994 – 1996 NORTHERN STRAIT OF GEORGIA OYSTER SURVEY

by

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ABSTRACT

Accurate assessment of shellfish populations is integral to effective stock management. Estimates of current inventories, and predictions of future stocks are desired by inventory managers.

The northern Strait of Georgia wild oyster survey was the result of concerns regarding the possible over-harvest of oyster populations. The survey was conducted over a period of three years from 1994 to 1996 by a survey team commissioned by the Klahoose first nations, and was located in the Desolation Sound area of the south-central coast of British Columbia. The purpose of the survey was to examine the growth patterns of the incumbent wild oyster population.

The goals of this paper are twofold. The first goal is to provide a comprehensive analysis of the data collected over the three years of the study. The second goal is to examine the survey design in order to determine optimal sampling techniques which could be used in future studies.

Acknowledgments

I would like to thank the faculty, staff, and my fellow graduate students at Simon Fraser University who have helped to make my experience for the last few years as rich as it has been. I am particularly grateful to my supervisor, Dr. Carl Schwarz for his guidance and patience, and to my fellow students Colin MacLeod and Derek Bingham for their encouragement and support.

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Chapter 1

Introduction

Wild, self-maintained populations of the introduced Pacific oyster (*Crassostrea gigas*) are spread widely throughout the territories of the Klahoose and Sliammon First Nations in the northern Strait of Georgia and adjacent waters of British Columbia. Pacific oysters are harvested both commercially for domestic and foreign sale and non-commercially as a food fishery. During recent years, the commercial Pacific oyster fishery in British Columbia has had an annual harvest of around 5,000 metric tonnes with a "farmgate" value of between 5 and 6 million dollars;[*] while estimates of non-commercial harvests are unavailable, they are believed to be much lower.

In 1994, as part of the negotiations of a Joint Stewardship Agreement between the Alliance Tribal Council of the Klahoose and Sliammon First Nations and the British Columbia Ministry of Agriculture, Fisheries and Food, discussions were held regarding co-management of the existing oyster populations within First Nations' territories. The First Nations representatives felt that the wild oyster harvest was excessive, and that harvest rates should be reduced to levels that provided long-term sustainability. In the course of these discussions it became apparent that many of the stock management decisions rested upon the poorly known details of year to year changes in abundance and

[*] <http://www.ncr.dfo.ca/communic/statistics/landings/S1995pve.htm>

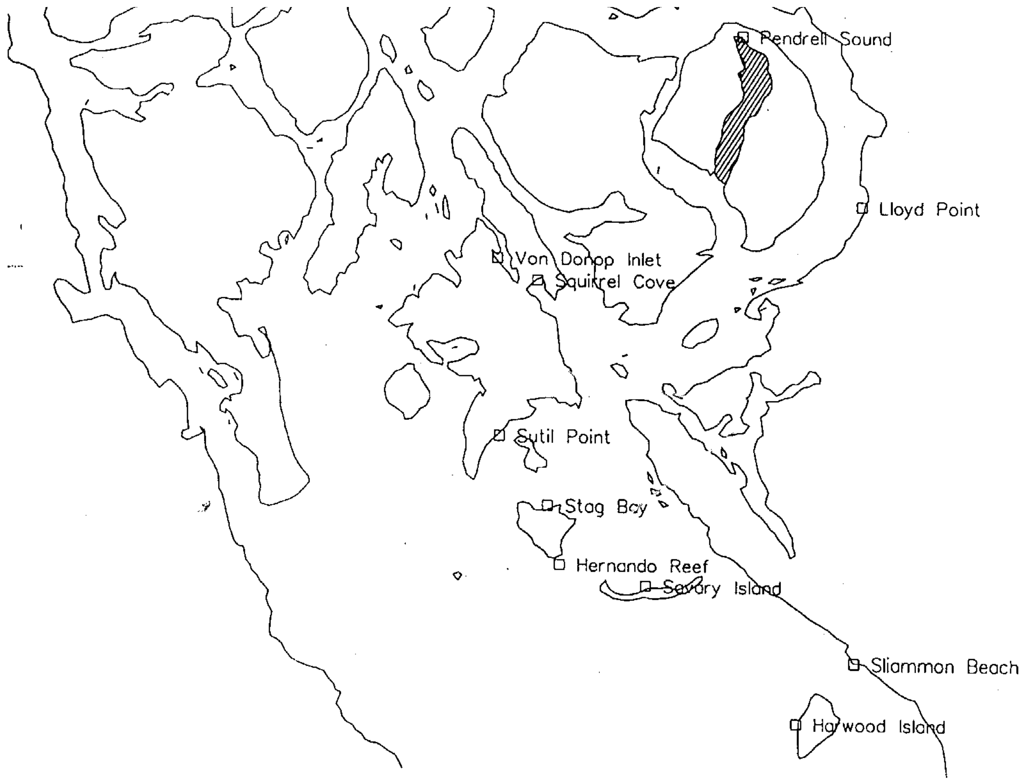

Figure 1.1: Map of Desolation Sound area of mid-south coastal British Columbia showing locations containing test plots (Morrell 1996).

size composition of oyster stocks. As part of an attempt to address questions regarding these details in the Klahoose and Sliammon territories, a three year study was initiated. The results of the individual years of the study have been reported by Morrell (1994, 1996, and 1997).

The study was conducted in the ten locations in the northern Strait of Georgia shown in Figure 1.1. All the field work was carried out by a team made up of Mike Morrell (field biologist), Dave Nikleva (fisheries coordinator for Klahoose First Nations), fishery staff members of the two First Nations, and other workers hired from the two communities. The study had three separate parts: population density, recruitment, and growth. The goal of the density study was to track changes in the densities of oysters by size and by weight. The aim of the recruitment study was to provide estimates of the amount of settlement of new spat (juvenile oysters). The growth study was designed to yield estimates of year-to-year growth of individual oysters.

The purposes of this report are to provide a comprehensive analysis of the data arising from the three years of the study and to examine whether a more efficient design could be incorporated into future studies.

1.1 Outline of the Three Surveys and their Protocols

The field work began on 20 July 1994. The field crew spent 3 days visiting all the study areas, making preliminary choices of plot locations. Within each of the ten locations shown in Figure 1.1, a permanent study plot was established. During this initial period a methodological protocol was established, and standard field data forms were developed. All the plots were located in known oyster habitat within the territories of the Klahoose and Sliammon First Nations.

It is important to emphasize that the plots were not selected with the intention of using them to estimate oyster densities or total populations over a larger area. The plots were chosen to study population processes (recruitment, growth and mortality). The study designers hope that the results will provide valid indices of rates of population change for each study area. If the objective had been to estimate average densities and total standing stock over a large area, the method of plot selection would have been quite different.

1.1.1 Density Survey

For the density part of the study, oyster populations on the study plots were sampled in order to estimate population densities by weight and by numbers in each of 5 size classes. Plot locations were selected in 1994 in areas known to be good oyster habitat. The areas that were chosen were ones that the field workers thought would be subject to a range of different harvest rates (based on accessibility, degree of pollution and proximity of settlements). Within those areas they selected patches of fairly homogeneous habitat and oyster density. The goal was to have plots in which they could efficiently measure the population variables of interest with high precision with a reasonable amount of sampling effort.

Most plots were approximately rectangular or oval in shape and measured 100m or more along the long axis; the surveyors attempted to include 1000 to 2000 square metres of area in each plot. Where oysters occurred in discrete patches of about the right size (Stag Bay, Pendrell Sound), they included entire patches. Where oysters were distributed in bands along the shore (Lloyd Point, Squirrel Cove Bay, Von Donop Inlet), they chose the long axis of the plot parallel to the shoreline in order to encompass appropriate habitat and determined the plot width on the basis of oyster distribution. Additionally, in plots where the edge was clearly defined, the lateral boundary was chosen to be a line past which no oysters were visible. In plots where the edge was not clearly defined, the lateral boundary was chosen by eye so as to include within the plot boundary approximately 95% of the available oysters. Where oysters were more or less uniformly distributed over an area much larger than the preferred plot size (Sutil Point East, Hernando Reef, Siammon Beach, Harwood Island, Savary Island), the surveyors laid out rectangular plots of uniform width within the larger area.

The data collection took place at a rate of one plot per field day on the lower low tides from late July until early September. At each plot a crew of 3 to 5 people collected the data according to the following protocol: On arrival at the study plot on the falling tide, they either first established a central traverse line of the plot along the long axis and placed permanent markers at each end (in the first year), or they relocated this line (in the following two years). Using a random number table, they then selected a starting point

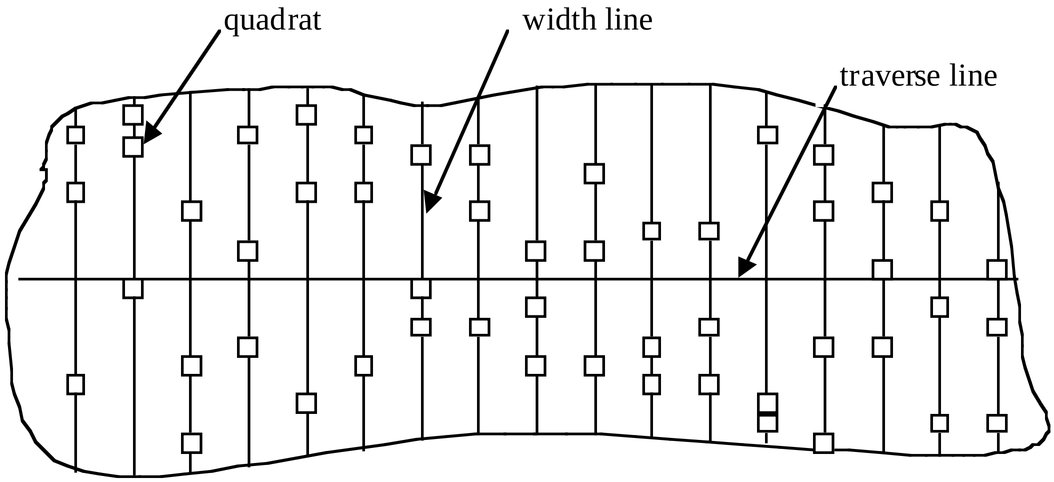

Figure 1.2: Schematic showing sampling plan at a study plot.

from the length, say L, of the fixed interval used in the plot (usually 10 metres). They then marked a series of points along this line every L metres. At each of the marked points along the traverse line, they measured the plot width along a line perpendicular to the centre line. Along each width line they chose a predetermined number of points (usually three, but occasionally up to six) at random using a table of random numbers and located a quadrat of 0.25 or 1 square metre at each of the selected points. A schematic of the sampling plan is shown in Figure 1.2.

Within each quadrat, all the oysters were collected and classified into five size categories on the basis of the longest shell dimension. The size categories used were the same as the system used for classifying oysters for market. These size classes are seed, extra small, small, medium, and large; which correspond to sizes of less than two inches, between two and three inches, between three and four inches, between four and five inches, and greater than five inches respectively. For each quadrat, the number in each size class and the total weight of all the oysters not including the smallest size class was recorded. A sample data form is shown in Figure 1.3.

Figure 1.3: Sample data form used in the density survey.

1.1.2 Recruitment Survey

In each of the first two years of the study, the field crews set out 30 Vexar plastic mesh bags of clean oyster shell cultch ("spat-catchers") along the centre line of each plot to provide a substrate upon which oyster spat might settle. In 1995 the crews retrieved either ten, or half of the spat-catchers that could be located, and left the remainder for 1996. At that time, they also distributed another 30 spat-catchers on each of the plots. In 1996, the crews retrieved at least 10 spat-catchers from each of the plots.

The spat-catchers from each site were processed separately. All the Vexar bags were opened, and then broken and very small cultch shells (those smaller than 75 mm) were set aside. From the remaining shells, random samples (with equal numbers from each of the bags in a plot) of between 70 and 130 shells were taken. All the seed oyster on each of the selected shells were then counted. The surveyors also measured the lengths of seed oysters on the cultch (using digital calipers to the nearest 0.1 mm) until a target number of lengths was achieved. This target was 240 in 1995 and 120 in 1996. A sample data form is shown in Figure 1.4.

1.1.3 Growth Survey

This experiment was conducted with the goal of measuring the growth of individual oysters. This study was conceived later, and did not commence until 1995. In that year, a total of 48 oysters were selected from areas close to the test plots. These 48 oysters were selected so that there were twelve each with maximum length measurements of as close as practically possible to 51, 76, 102, and 127 mm (one inch intervals from two to five inches inclusive). These oysters were then each marked with numbered plastic tags attached with stainless steel wire through a hole drilled through the umbro of the shell. They were measured to the nearest 0.1 mm and three from each size class were placed in Vexar bags.

Figure 1.4: Sample data form used in the recruitment survey.

Figure 1.5: Sample data form used in the growth survey.

The bags were laced closed and stapled adjacent to the plot, two at each end of the centre line.

In 1996, the field crew located the bags, then measured and replaced the tagged oysters. Any dead oysters were replaced with newly tagged ones of the appropriate size collected from near the plot. In addition, crews added three new tagged oysters in the smallest size class (around 51 mm). In 1997, the bags were again located and all the oysters were measured. A sample data form is shown in Figure 1.5.

1.2 Data Problems

For a first-time study of this size and scope, it would be unusual for there to be no problems with the data. This project was not unusual, although most of the problems that did arise were of the type that were resolved with re-examination of the original data sheets, and by consultation with the field workers. There were three problems however that are worth reporting in detail, and which are listed below.

The first problem was that in the first year of the study, two unforeseen issues arose which were dealt with by the principals of the study, but which resulted in some small differences in the data between that year and the following two. The first issue was that, during the first year of the density study, the counts of oysters of less than one inch, and between one and two inches were recorded separately. In years two and three of the study, the smallest size category included all oysters smaller than two inches. The second change was that for the first year, in four of the locations, the quadrat size used in sampling was one square metre, while in the others it was 0.25 square metres. In the latter two years, the quadrat size was standardized to be 0.25 square metres for all the locations. In order to standardize the data, the measurements for the one square metre quadrats were all divided by four. The implications of doing this will be discussed briefly in the next chapter.

The second problem occurred at the Savary Island test plot. In this location during 1995 (the second year) there was some confusion in the recording of the weights for the density data. Some of the records included the weight of the weighing pan, while other records were net of the weight of the pan. Unfortunately, despite the concerted efforts of this author, the field biologist, and the fishery coordinator for the two First Nations, this data problem could not be resolved and this portion of the weight part of the density data had to be excluded from the analysis.

The third set of problems were perhaps the most damaging to the project. During the second and third years of the growth study, it became clear that there was a serious flaw in its design. Upon removing the tagged oysters from the Vexar bags and measuring them, it was evident that many of them had not grown larger, and had in fact become smaller. This problem was caused by abrasion due to the winter storms that are experienced in this area. Compounding these difficulties were problems with missing Vexar bags of oysters and high mortality rates of oysters in certain bags (likely because they were more exposed). Of the 480 oysters tagged and bagged in the first year, only 126 were retrieved in the second year. Preliminary results from this part of the study will be presented in Chapter 4 where it will be evident that unfortunately, no meaningful conclusions are available for this part of the study.

Chapter 2

Density Data Analysis

This chapter will detail the exploration and the resulting analysis of the density data for both the counts of oysters present by size class and the total weight of oysters in the quadrat. In both cases, a model for analysis will be developed and evaluated. Additionally, both the count and weight data will be analyzed together with the weight serving as the response variable and the count data serving as the predictor variables.

2.1 Analysis of the count data

Figure 2.1 shows the mean density for each of the 150 location by year by size class combinations. In order to help us understand the reasons behind the differences in the densities that are apparent in Figure 2.1, one approach is to fit the data to a model that includes the factors that interest us such as year, location, their interaction, and possibly others as explanatory variables.

Before fitting a model, it is first necessary to examine the data for homoscedasticity – i.e. is the variability of the data the same regardless of the mean density (or some other factor). This evaluation was conducted using a simple technique whereby the sample mean and sample standard deviation were calculated for each of the 150 combinations. The resulting 150 pairs of numbers were then plotted as shown in Figure 2.2.

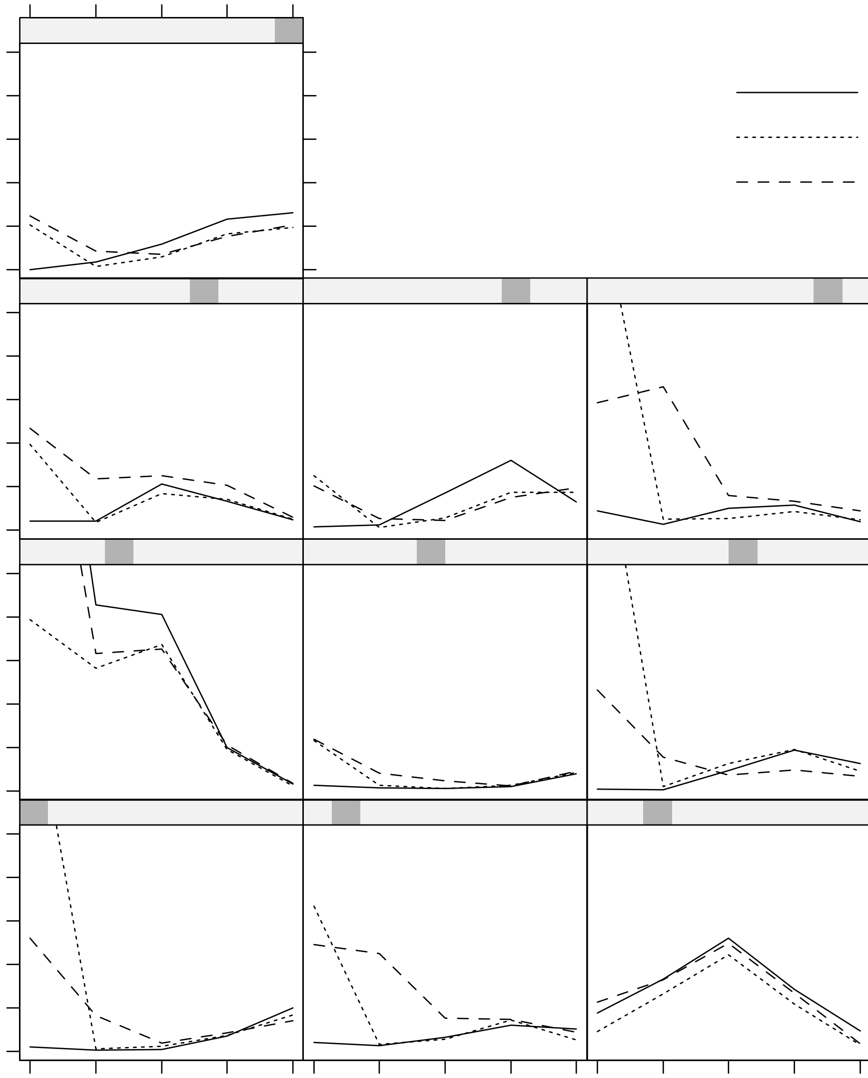

Figure 2.1: Plot of mean density per square metre calculated separately for each of the 150 year by location by size class combinations. Each line represents a year. Each sub-plot is for one location.

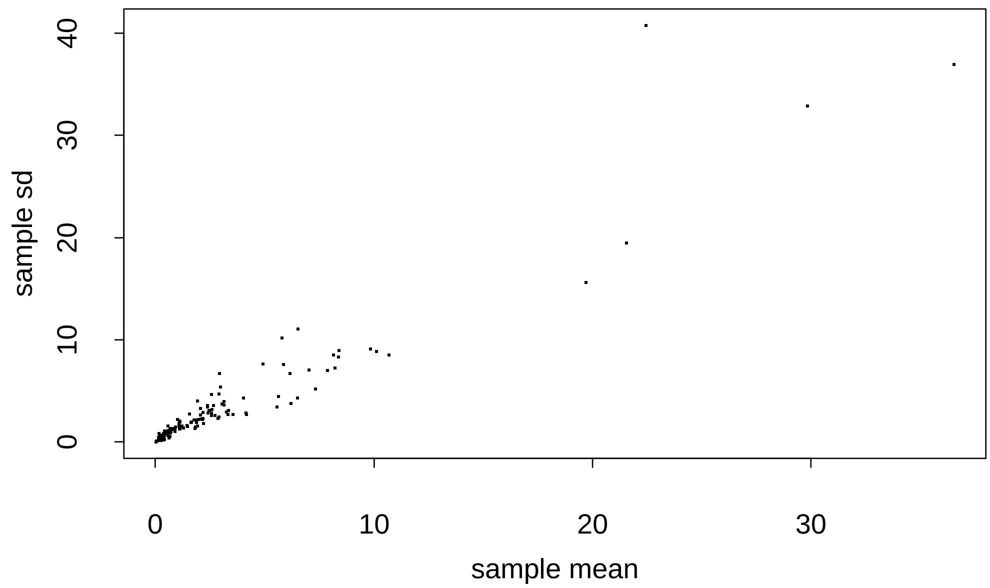

Figure 2.2: Plot of sample standard deviation against sample mean for all 150 year by location by size class combinations.

The clear upward trend indicated by the points in Figure 2.2 reveals that the usual regression / ANOVA analysis using linear modeling techniques is not appropriate with this data (the estimates are still unbiased, but not fully efficient). In order to analyze this data using classical linear modeling techniques (as requested by the clients), it is necessary to transform the data so that the resulting data is homoscedastic, and at least approximately normally distributed. An appropriate transformation should be suggested by theoretical considerations – if our knowledge of the data provides us with them. In this case, since the data are made up of counts of oysters in fixed area quadrats, it would be more natural to assume that they follow a Poisson rather than a normal distribution. It is also however that the data itself should suggest an appropriate transformation.

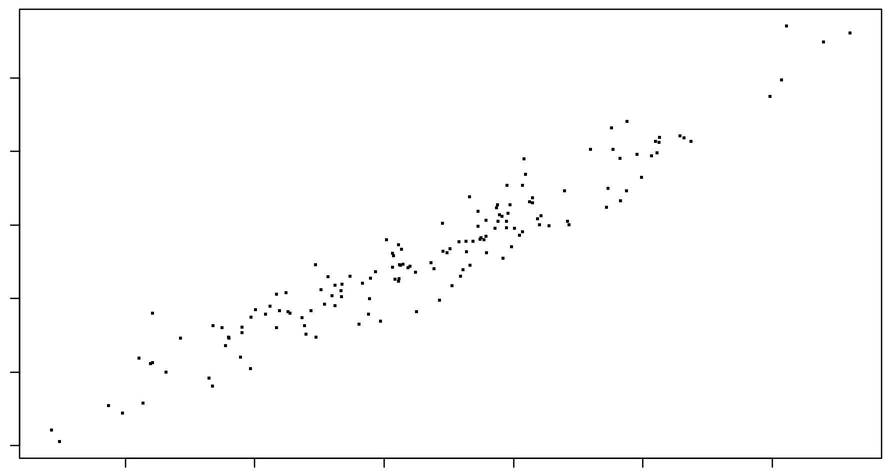

Figure 2.3: Plot of log(sample standard deviation) against log(sample mean) for all 150 year by location by size class combinations.

To aid us in finding the relationship between the mean and variance (which will indicate an appropriate transformation), logarithms of these values are plotted against each other as shown in Figure 2.3. Montgomery (1997) advises that a slope of one in this graph indicates a logarithmic transformation of the data is appropriate, while a slope of one-half implies a square-root transformation. See Hinkelmann and Kempthorne (1994) for a complete discussion of variance stabilizing transformations. One can see from the graph that the slope lies somewhere in between these two values. In fact, a least-squares fitted line through these points has a slope of approximately 0.80. It might be suggested that a fractional root transformation would be appropriate. However, the clients felt that this would be somewhat arbitrary and not easily understood, and volunteered a preference for either a square-root transformation, or a logarithmic transformation.

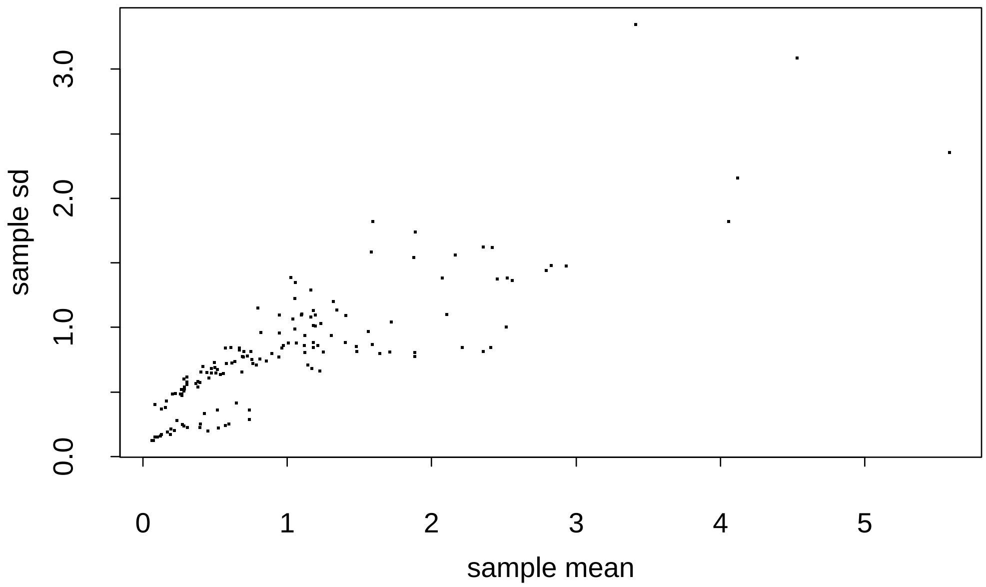

Figure 2.4: Plot of sample standard deviation against sample mean for all 150 year by location by size class combinations after square root transformation of the data.

As a brief aside, the point mentione in the introduction regarding standardizing this data so that all the measurements are per quarter square metre should be addressed. It is unlikely that the relationship between the mean and the variance is preserved by this standardization. This is unfortunate, but within the confines of the linear model framework there is little else that can be done.

In deciding which of the two transformations to choose, the simplest and most practical approach is to choose the one that stabilizes the variance most effectively. Figures 2.4 and 2.5 show resulting plots of sample standard deviation against sample mean after the data has been subjected to the square root and the logarithmic transformations respectively. As the logarithm of zero is not defined, the convention of adding the smallest observable non-zero value to each observation before taking the logarithm is followed. In this particular case, that smallest non-zero value is 0.25, due to the earlier discussed

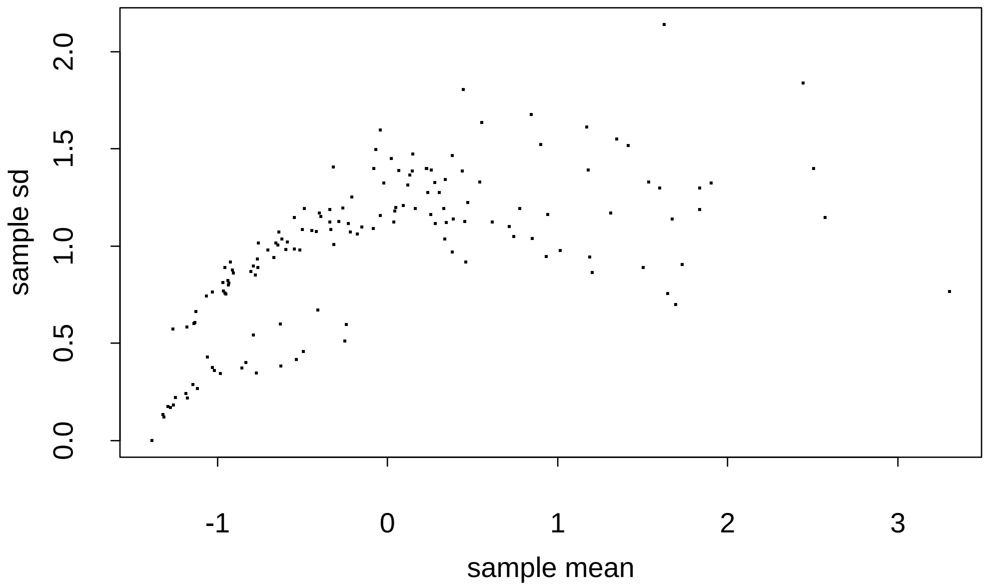

Figure 2.5: Plot of sample standard deviation against sample mean for all 150 year by location by size class combinations after logarithmic transformation of the data.

quadrat size problem. It is evident from the plots that although neither of the two transformations is extremely effectual in stabilizing the variance, the logarithmic transformation is at least slightly better than the square-root transformation. Hence, the logarithmic transformation is chosen.

In fitting a model to the data, the task is first simplified by fitting a separate model for each size class. Next, the factors to be included in the model are selected. Three factors that are chosen for inclusion and examined for their significance are location, year, and their interaction. Furthermore, since traverse points are representative of the density at particular points along the length of the oyster bed, that factor is also included in the model. Because the effects of the first three factors listed above are for particular locations and times, they are taken to be fixed effects; and because the traverse points along length of the oyster bed were not chosen to be representative of any particular point, the traverse location is taken to be a random effect. Additionally, because the random effect of traverses within different location and year combinations will not be the same, this factor is nested within each location and year combination.

Using the factors listed above, the following model is fitted separately for each of the five size classes:

$$\log(\text{Oyster}_{jklm} + .25) = \mu + L_j + Y_k + LY_{jk} + \tau_{jkl} + \varepsilon_{jklm}$$

where

Oyster_{jklm}	=	number of oysters in location *j*, during year *k*, in traverse *l*, at width point *m*;
μ	=	fixed effect due to size class;
L_j	=	fixed effect due to location j;
Y_k	=	fixed effect due to year k;
LY_{jk}	=	fixed effect due to the interaction between location j and year k;
τ_{jkl}	=	random effect due to the traverse point, distributed as $N(0,\sigma_{\mathrm{T}}^2)$;
ε_{jklm}	=	random effect representing all other sources of variation, distributed as $N(0,\sigma_{\varepsilon}^2)$;

and indices: $j =$ 1..10 (locations),

$k =$ 1..3(years),

$l =$ 1..T_{jk},(the number of traverse points within a particular year location);

$m =$ 1..W_{jkl} (the number of width points within a particular year, location, and traverse point).

All the effects were significant with exception of the year by location interaction term for size class four, which had a p-value of 0.65. Although the width point within traverse factor was not included in the model, examination of the residual graphs in appendix I makes it apparent, that this factor (and possibly its interaction with traverse) has significant effects upon the density of oysters. This effect that can vary considerably, even within the same location over years. Lurking variables such as vertical displacement from chart datum (a tide height of zero metres), or substrate type are likely confounded with width point, and future studies may find it fruitful to explore methods of including those variables within the scope of their study.

Because of the large number of parameters, examination of the numerical estimates of these parameters would be uninformative, and is not done here. It is instructive however, to examine the point estimates of median density per square metre of each location by year by size class combination resulting from this model. The reason that these estimates are for the median density is that they are derived by back-transforming the predicted means which are in the logarithmic scale. Figure 2.6 displays those estimates in graphical form, and table A.2.1 in Appendix II contains those estimates, as well as confidence intervals in tabular form. By examining Figure 2.6, the shapes of these curves can provide us with some clues regarding recruitment, mortality, and growth rates.

One of the common shapes is that of a horizontal sigmoid curve – a sideways ‘S’ shape. This is exhibited in the Sliammon Beach, Squirrel Cove Bay, and Stag Bay locations. The leftmost tail of the curve indicates recruitment. The drop of the curve in size class two (extra-small) is a result of the combined effects of seed mortality and a rapid absolute rate of growth for the oysters in this size range. The densities increase over the next two size classes (small and medium), indicating a slowing rate of growth and perhaps lower rates of mortality. The final downward slope of the rightmost part of the curve is a sign of mortality of the oysters in the large size class.

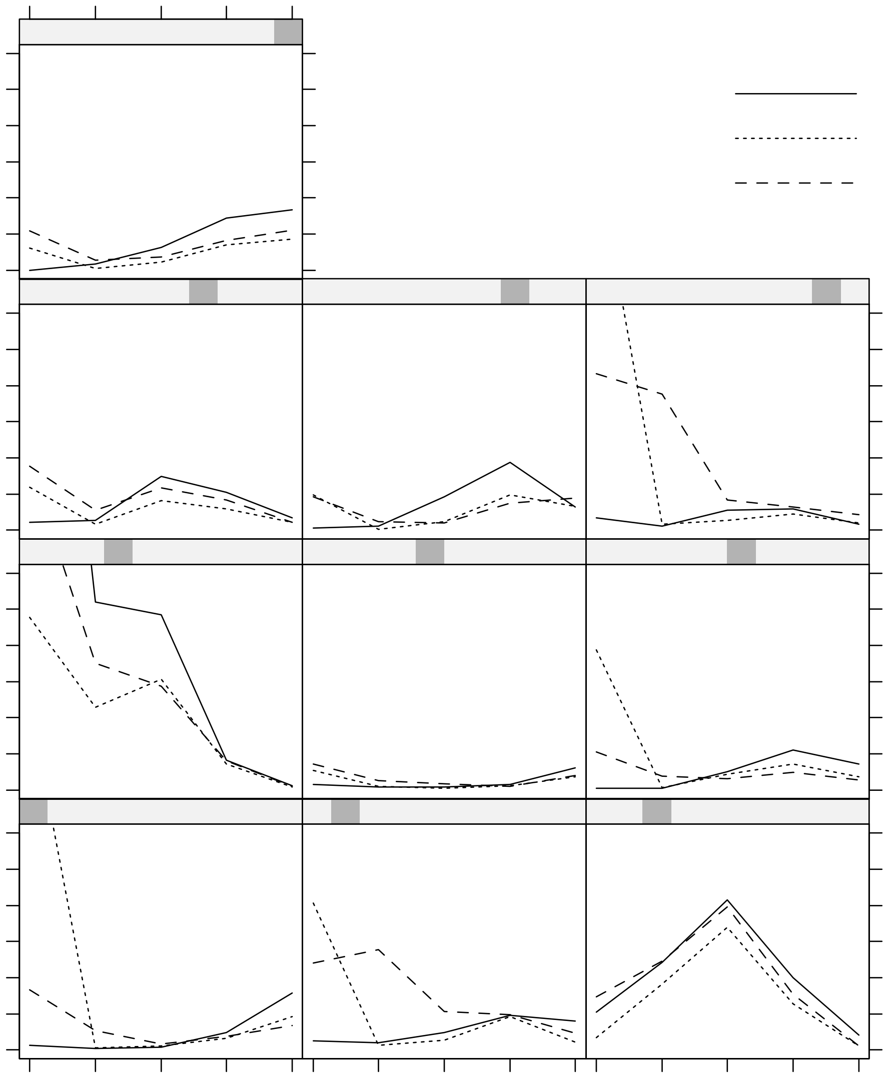

Figure 2.6: Point estimates of median density per square metre resulting from fitting a mixed-effects model to logarithmically transformed data. Each line represents a year. Each sub-plot is for one location.

Another common shape is that of a shallow saucer, or shallow ‘u’. This pattern might be seen in varying degrees in the Harwood Island, Savary Island, and Von Donop Inlet locations. These three locations all show decreases in density from the seed size class to a point which could be anywhere from size classes two to four, and then gradual increases up to the large size class.

Sutil Point East and Hernando Reef show some similarity, especially when one considers their changes in distribution over the three years. For the first two years, they both show size class distributions in the pattern of the horizontal sigmoid shape discussed above, but in the third year the leftmost part of the tail ‘flips around’ so that its slope is shallower.

As mentioned above in the discussion for Sutil Point East and Hernando Reef, it is possible to examine all these curves in order to identify changes over time. As an aid to judging whether apparent differences are truly significant Table A.2.2 in Appendix II lists the p-values which have not been adjusted for multiple comparisions for differences in density within each location over the years 1994-1995, and 1995-1996.

A simple approach to looking for changes over time is to identify "pulses" of high density, visible as peaks in Figure 2.6. Lloyd Point has an easily seen pulse which was progressing through size class three during the course of the three year survey. Also, in Stag Bay, Sutil Point East, Harwood Island, and Hernando Reef, a pulse can be seen that was apparent in size class one in 1995, and has partially progressed to size class two in 1996. Pendrell Sound on the other hand shows very high annual pulses and rapidly declining densities all the way down to virtually zero for the large size class. This represents the classic case of high and continual recruitment accompanied by high mortality.

Speculation is only possible at this time, but an interesting topic for a future study might be to examine whether the harvesting of the larger size-class oysters “makes room” for higher recruitment in the following years. On the other hand, 1994 may just have been a poor year for oyster recruitment. This last postulate is supported by the apparently modest recruitment in 1994 in the Sutil Point East oyster bed, and is contradicted by the very high densities of size class one and two oysters in the Pendrell Sound bed.

Additionally, Table 2.1 lists estimated percent of model variation attributable to all the effects in the model when all the effects are fitted in a completely random effects model. It is clear that as the size classes of the oysters increase, the overall variation decreases while the percent of variation unexplained by the model increases. This table also provides more specific suggestions regarding the sources of variability. The rapid decline in variability due to year and to the location by year interaction implies that temporal effects become less important as the oysters increase in size. The relatively constant proportion of overall variability attributable to traverse suggests that the within bed variability remains somewhat constant as the oysters grow larger. The large proportion of variation due to the location for size classes two and three is puzzling, but might be caused by the population dynamics being very different in Pendrell Sound and Lloyd Point. Table 2.1 also makes it clear that much of the variability in density has not been explained by the factors in the model.

Size Class	% due to Loc	% due to Year	% due to Loc*Year	% due to Traverse	% due to Residual	Total Variation
1	13.7	16.1	19.3	8.2	42.6	3.40
2	31.0	9.4	10.4	8.0	41.2	2.09
3	38.3	1.5	3.1	6.6	50.6	1.85
4	14.1	1.7	0.0	11.2	73.0	1.47
5	16.5	2.3	2.1	9.5	69.5	1.40

Table 2.1: Percent variation explained by individual components when a completely random effects model is fitted.

2.2 Analysis of the weight data

The process of analyzing the total weight of oysters in the quadrat data used the same ideas as the analysis of the count data. The weight data was first examined for homoscedasticity by plotting the sample mean and sample standard deviation of the weight for each of the year by location combinations as seen in Figure 2.7.

An upward trend is clearly evident in Figure 2.7. This upward trend is supported by Figure 2.8, a plot of the log(sample means) versus the log(sample standard deviations) of each year by location combination. This time, a least-squares fitted line through these points has a slope of 0.76. That this relationship between the mean and standard deviation is so similar to that of the counts data is not surprising, since these weight data will be greatly influenced by counts of the two heaviest size class oysters – both of which exhibited a relationship between the mean and standard deviation. Therefore, as before, a transformation will be necessary in order to use the classical linear modeling techniques. Figure 2.9 shows the plot of sample mean versus sample standard deviation of all the year by location groups after performing a logarithmic transformation of the data. Because the dataset contains quadrats with a weight of zero, it is necessary to first add the smallest observable weight value of 0.05 kg to all the weights before calculating the logarithm. Although Figure 2.9 shows that this transform has not stabilized the variance perfectly, it is an improvement over the earlier situation in that the relationship between the mean and standard deviation is not as clear-cut.

The model fitted for the weight data is:

$$\log(W_{jklm} + .05) = \mu + L_j + Y_k + LY_{jk} + \tau_{jkl} + \varepsilon_{jklm}$$

where W_{jklm} signifies the weight of the oysters in in location *j*, during year *k*, in traverse *l*, at width point *m*, and the remainder of the descriptions of the effects are the same as for the counts data analysis.

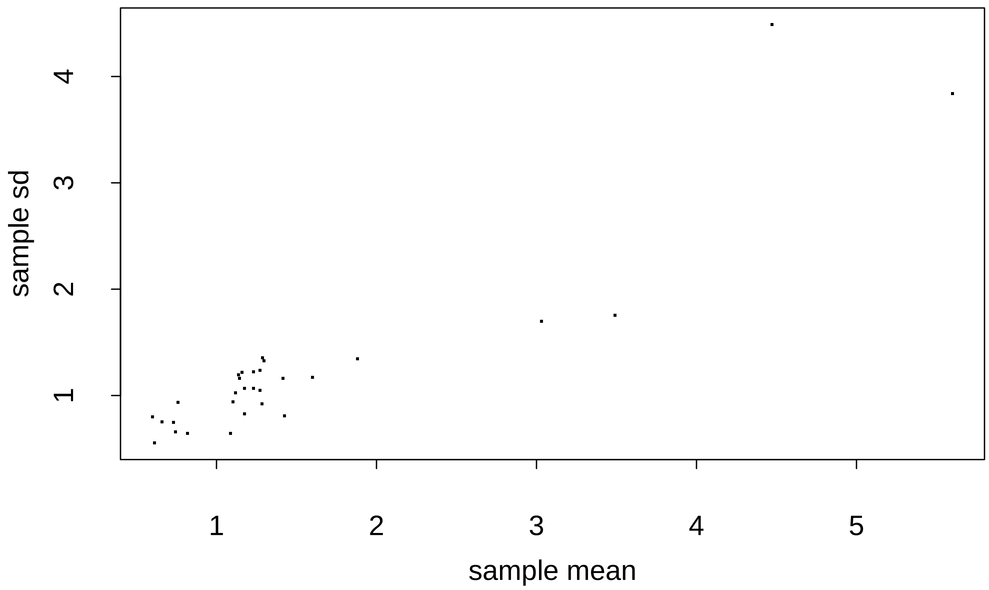

Figure 2.7: Plot of sample standard deviation against sample mean for the 30 year by location combinations of the weight data.

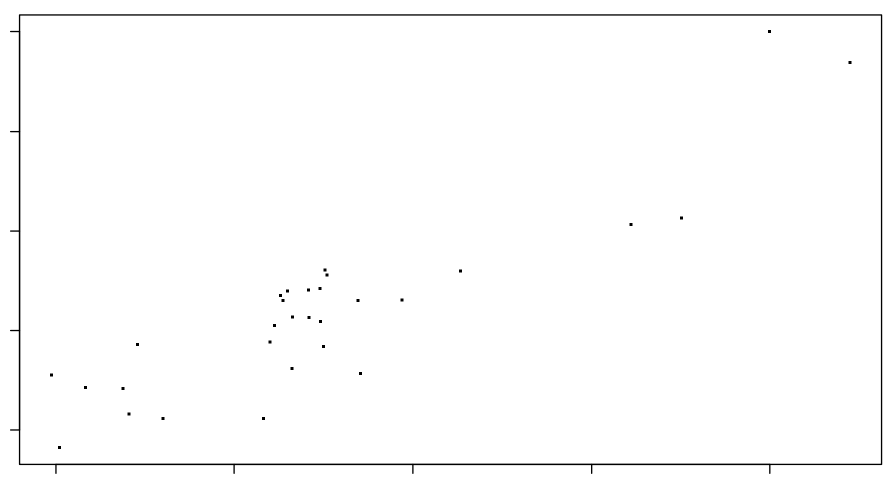

Figure 2.8: Plot of log(sample standard deviation) against log(sample mean) for the 30 year by location combinations of the weight data.

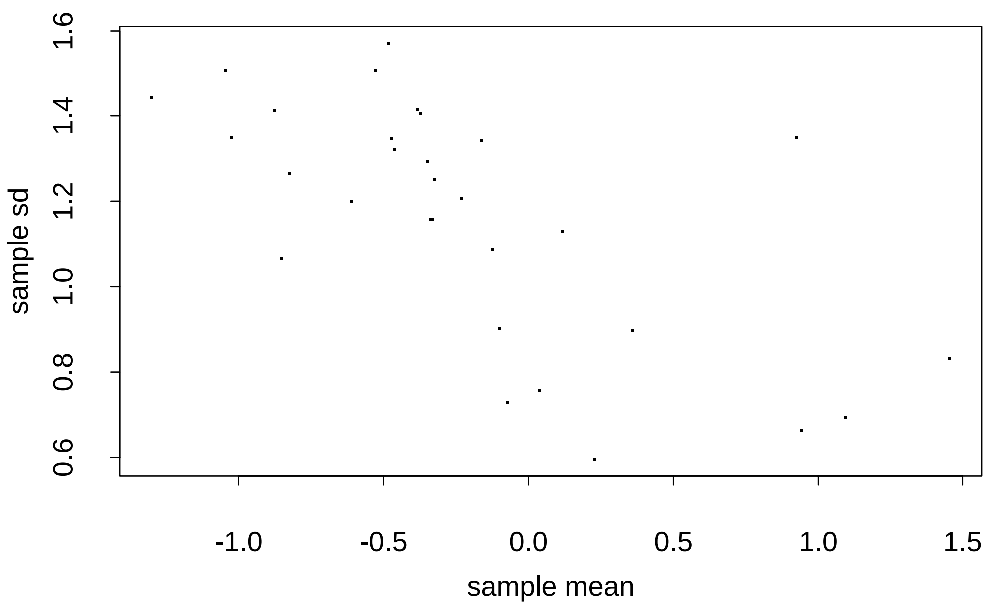

Figure 2.9: Plot of sample standard deviation against sample mean for the 30 year by location combinations of the weight data after a logarithmic transformation of the data.

The results of fitting this model are slightly different than when the counts data was analyzed. The effects of location and year are both significant. However, the location by year interaction effect is not significant, with a p-value of 0.15. One possible interpretation of this lack of significance is that the biomass capacity of a particular location and year is invariant to differences due to changes in individual size class compositions which are caused in part by harvesting, as well as other sources of mortality. This would be encouraging in terms of harvesting, in that it might suggest that removals from an oyster bed would be quickly regenerated.

As was done before, point estimates of median weight per square metre have been computed, with the results displayed graphically in Figure 2.10, and in tabular form (with associated confidence intervals) in Table A.3.1 in Appendix III. Also, Table A.3.2 contains p-values for differences in weight within locations between years The results shown in Figure 2.10 are generally in accordance with the results of the count analysis. For example, the locations that showed a statistically significant drop in density of medium and large sized oysters between 1994 and 1995 show a corresponding drop in biomass per square metre, although as can be seen in Table A.3.2, the only significant differences for a one year change are Von Donop Inlet 94-95, and Hernando Reef and Sutil Point East for 95-96. This last point could possibly provide additional support for the thesis for the invariance of the biomass in a particular location and year.

2.3 Analysis of the joint count and weight data together

In this subsection a linear model is fitted which links the number of oysters in the four largest size classes to the weight measured. This regression will yield estimated average weight per oyster. The following model is fitted:

$$W_{jkl} = L_j \mid Y_k \mid (X_1 + X_2 + X_3 + X_4 + X_5) + \varepsilon_{jkl}$$

where,

W_{jkl} = weight of oysters in location j, during year k, in quadrat l;

L_j = fixed effect due to location *j*;

Y_k = fixed effect due to year *k*;

X_m = Number of oysters of size class *m*.

ε_{jkl} = random effect on size class, and is distributed as $N(0, \sigma_{\varepsilon}^2)$;

and indices: j = 1..10 (locations),

k = 1..3(years),

l = 1..T_{jk},(the number of quadrats within a particular year and location);

In the formula above, the '|' (pipe) notation indicates that both terms on each side of the pipe as well as their interaction are included, and is not an indication of a nested design. The results of this regression are that nearly all the effects are significant when tested at the

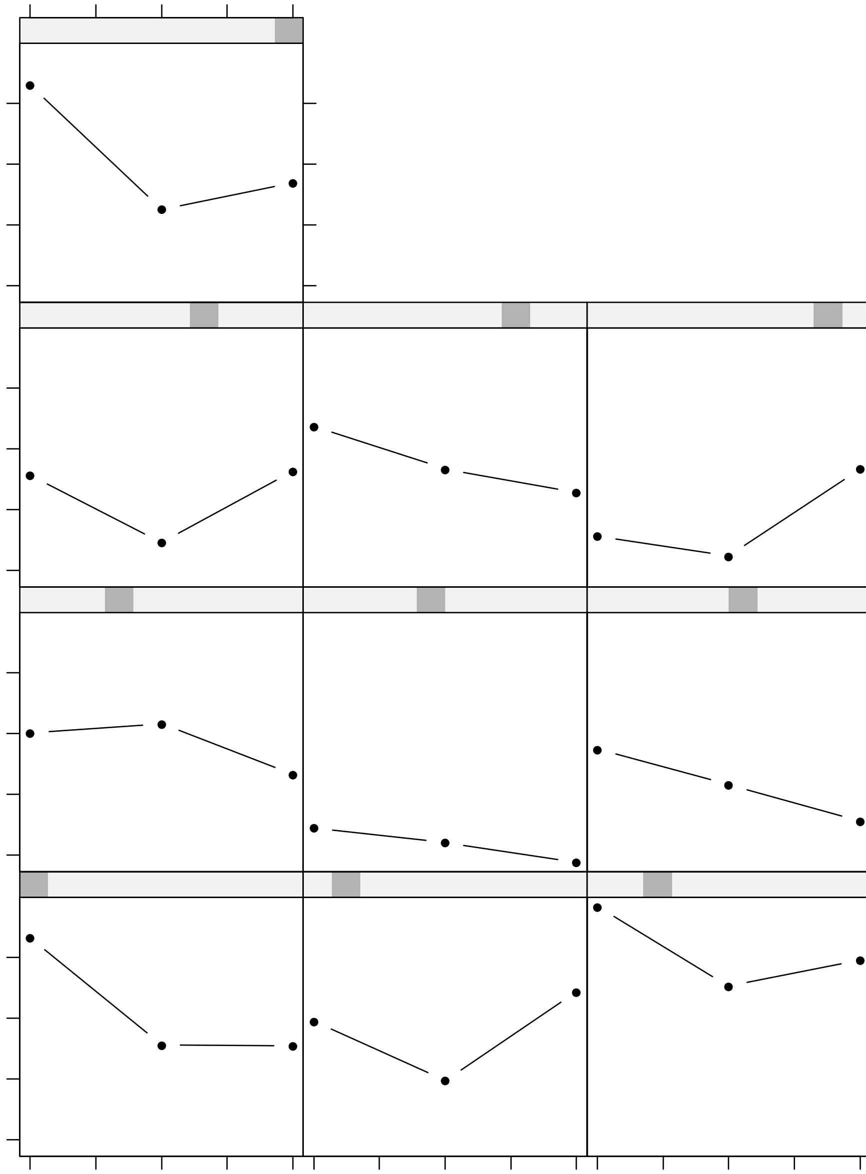

Figure 2.10: Point estimates of median weight per square metre resulting from fitting a mixed-effects model to logarithmically transformed data.

five percent significance level, exceptions being the effects due to location and to the location by year interaction and the coefficients for extra-small by location, small by year, medium by year, and small by location by year. However, by far the most significant contributions to the model are from the coefficients of the two largest size classes and of the large class size by location interaction.

Figure 2.11 shows the coefficients of weight per medium and large size oyster (with lines connecting the same years) resulting from fitting a separate model for each location. Note the missing point for Savary Island in 1995 due to the data errors discussed in the Introduction. To provide an indication of the variability, an average (over the three years) standard error bar is also plotted for each location. Most standard errors were in the range of .01 to .03, with some notable exceptions being for the coefficient of large oysters in 1994 and 1995 in Pendrell Sound (both around .07), and for medium oysters in Harwood Island in 1994 (around .07), and Savary Island in 1996 (around .08).

These graphs seem to show that the weight per oyster is fairly constant within locations over years for these two size classes. Some visible exceptions for the medium oysters appear to be in 1994 at Hernando Reef and Lloyd Point, and in 1996 at Squirrel Cove. For the large oysters, changes in the weight-size relationship might have taken place in 1996 at Sliammon Beach. These differences may have been caused by natural phenomena, or by selective harvesting.

In Figure 2.12, the coefficients for each of the size classes in each location have been averaged over three years. A typical error bar has also been plotted at the top of the graph to give some idea of the variability. Most of the standard errors are close to the ones pictured, with some notable exceptions being those for Harwood Island, which were as high as .23 and .19 for size classes two and three respectively, and at Sliammon Beach which had a standard error of .17 for size class three. It is also worth mentioning that

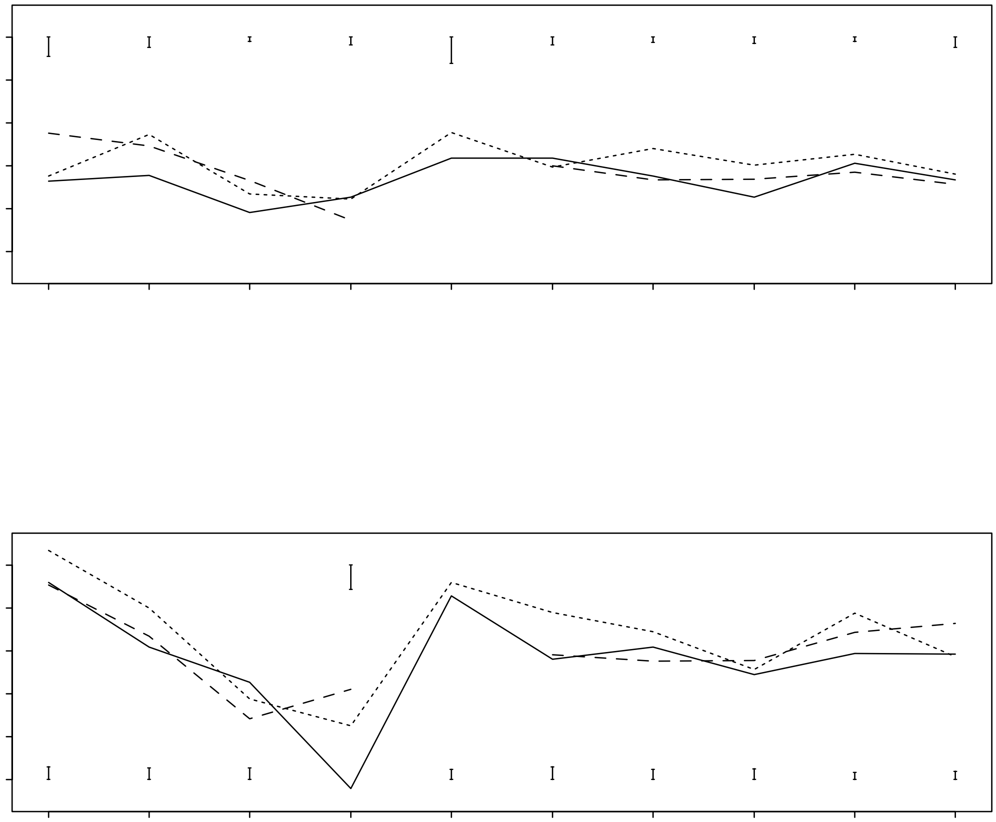

Figure 2.11: Estimates of average weight per medium and large size oyster (size classes 4 and 5) over all locations and years with typical standard error bars for each location.

although the coefficient for size class two at Savary Island was negative with a value of -0.066, it had a standard error of 0.33.

Figure 2.12 also provides some indication of whether different locations have different weight-size relationships. It appears that for size classes two, three and four, there may not be great differences in this relationship. For size class five however, Harwood and Savary Islands may have a higher average weight per oyster and Lloyd Point and Pendrell

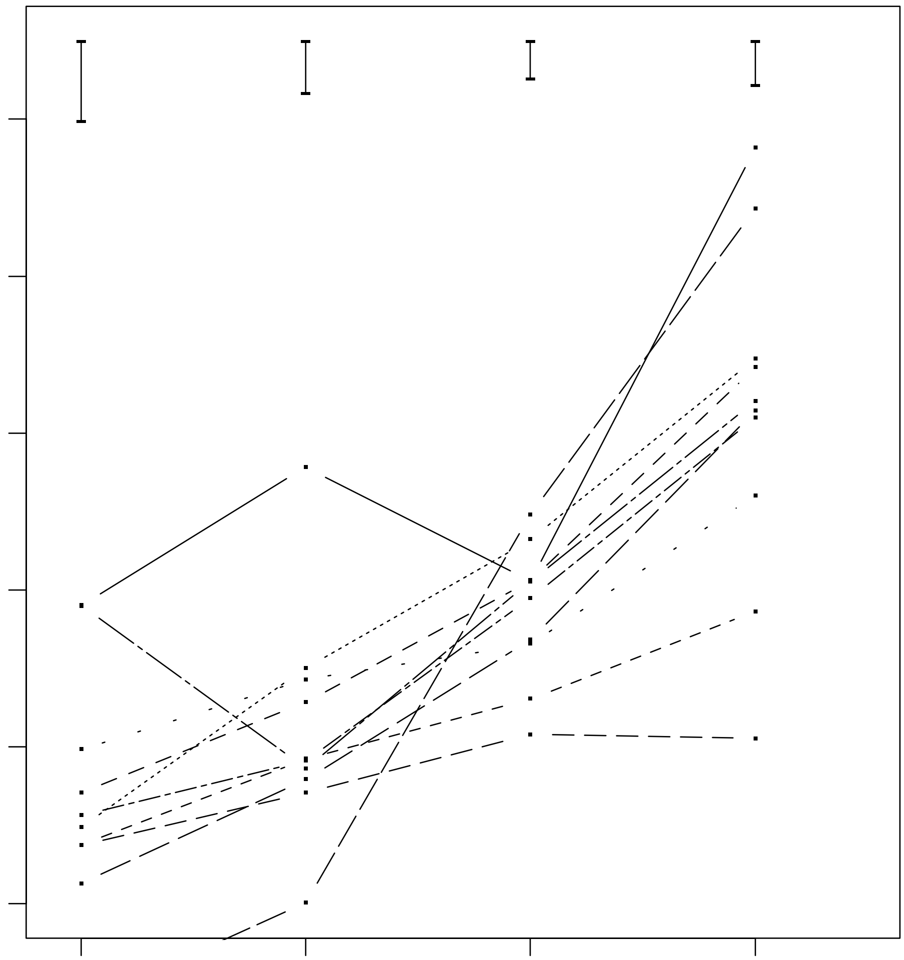

Figure 2.12: Coefficients of weight per oyster by size class with lines joining locations with bars showing typical standard errors.

Sound may have a lower average weight per oyster. These results are not terribly surprising since the large size class is open-ended, and natural constraints as well as harvesting will have the most dramatic effects on the weight-size relationship.

2.4 Summary

For the data on counts of oysters, both similarities and differences were found in the distribution of oysters within size classes between locations. At present however, the model only explains between 27 and 59 percent of the variability in the counts of oysters – indicating some room for improvement. There may be some indication that removal of numbers of larger oysters encourages the settlement of seed oysters. This last hypothesis might be supported by the relatively stable weight densities within locations. Finally, the weight-size relationship seems somewhat similar between locations for all but the largest size class.

Chapter 3

Recruitment Data Analysis

This chapter will explain the analyses performed on the counts and the lengths parts of the recruitment data.

3.1 Analysis of the count data

Preliminary analysis of the count part of the recruitment data reveals that the mean and standard deviation are associated and that a logarithmic-transform is appropriate. The model chosen to fit to this data is:

$$\log(\text{count}_{jklm} + 1) = \mu + L_j + Y_k + LY_{jk} + \tau_{jkl} + \varepsilon_{jklm}$$

where count_{jklm} signifies the count of the oysters in in location j, during year k, in vexar bag l, and for shell m, the three capitalized factors signify fixed effects due to location, year, and their interaction respectively, τ_{jkl} signifies the random effect due to the vexar bag, and ε_{jklm} is the residual variation.

All three of the fixed effects in this model were found to be highly significant. Additionally, roughly 25% of the overall variation is explained by the random effect of the vexar bag. Figure 3.1 shows graphically the back-transformed fitted values resulting from this model. The left end of each horizontal bar indicates the year of deployment, and the right end of each bar indicates the year of retrieval. The only non-significant change within

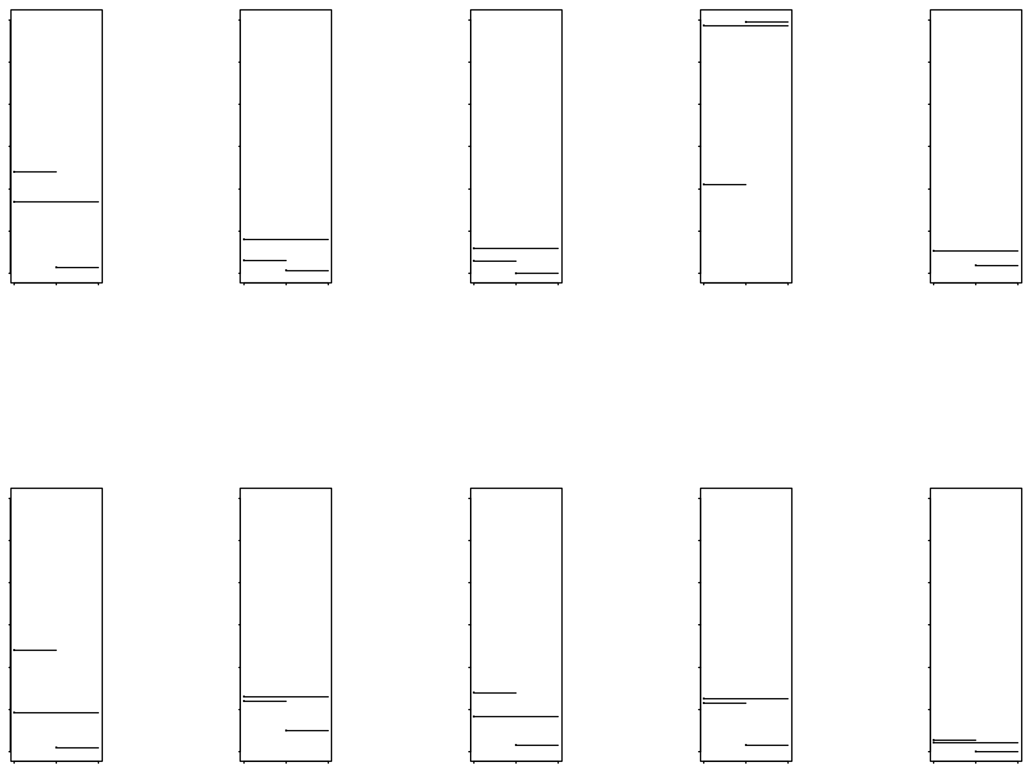

Figure 3.1: Median settlement of oysters per shell over one and two years for all locations. Each horizontal line indicates the time period encompassed by the estimate.

location when comparing 94-95 to 95-96 counts of settlement (number of newly arrived oysters) was at Hernando Reef (p-value = .16). This corresponds to the graphs in that most locations seem to show a clear difference in the level of recruitment between 94-95 and 95-96.

Comparision of the two-year settlement level (the wide bar) with the two one-year settlement levels shows that the process of oyster settlement is not strictly additive. In fact, in five of the nine locations that have all three data subsets, the two-year settlement level falls between the two one-year settlement levels. The reason for this might be that the numerical carrying capacity of an area could decrease as the oysters increase in size.

It is interesting to compare the results of this part of this part of the study with those of the counts part of the density survey. One would hope that years with relatively large measures of recruitment – density of seed (size class one) oysters in the density survey, and numbers per shell in the recruitment survey – would correspond for both surveys. In general, this is found to be true: Harwood Island and Sliammon Beach for example, both had a much higher density of seed oysters in 1995 than 1996, and both had much larger settlement counts in the 94-95 period than in the 95-96 period. However there is not always a correspondence - as in the cases of Squirrel Cove and Lloyd Point for instance, both these locations seem to reveal conflicting information in that the results from the density survey show a lower density of seed oysters in 1995 than 1996, but the results of the recruitment survey show higher numbers in the 94-95 period than in the 95-96 period.

3.2 Analysis of the length data

Figure 3.2 below shows the average length for the oysters that were measured as part of the recruitment study. In most locations (exceptions being Hernando Reef and Sliammon Beach), the average length of the oysters after one year of growth seems to be about the same. It also appears that average length over two years of growth is roughly twice the one year length growth.

Figures 3.3 to 3.7 show the mean number of oysters per shell from 0 to 100 mm broken down into size classes with a width of 2.5 mm (note that the vertical scale varies between locations and that a number of locations without data have blank graphs) with a separate histogram for each period of oyster settlement. These graphs give a rough visual feel for the distribution of the growth within each location and time period. For each location, a fourth histogram has been constructed by subtracting the 95-96 one year growth

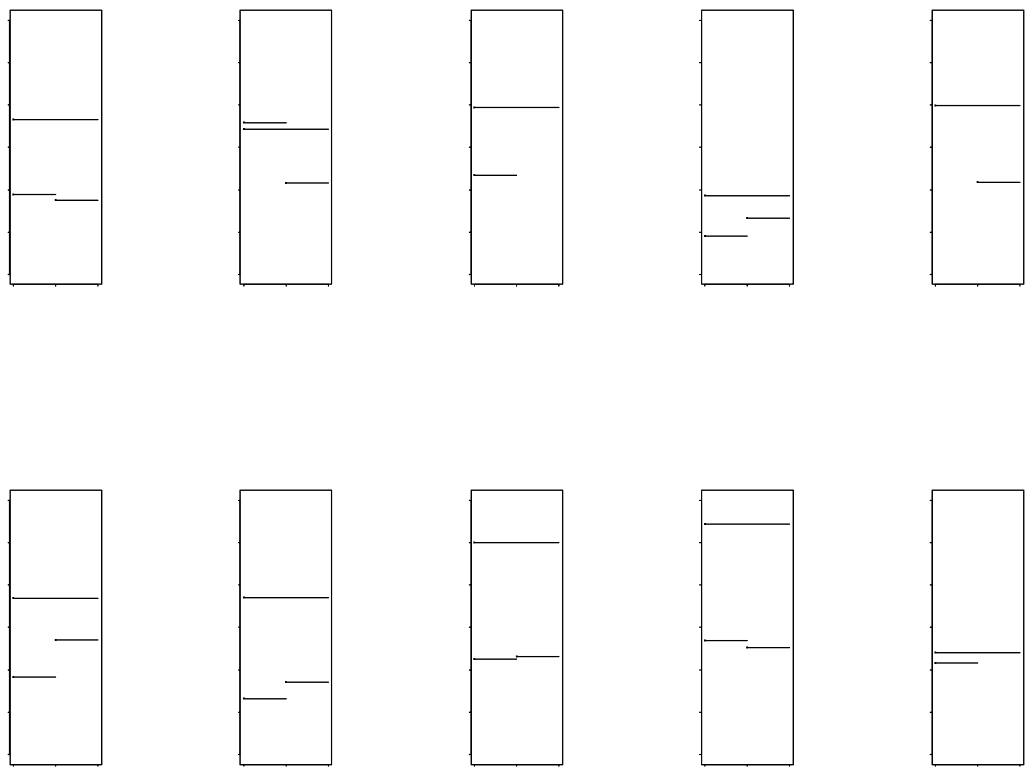

Figure 3.2: Average length of oysters with one and two year growth periods from 1994 to 1996. Each horizontal line indicates the time period encompassed by the estimate.

from the 94-96 two year growth (and zeroing any negative resulting numbers). This fourth histogram gives a very rough estimate for the growth of oysters in their second year of life in these locations over the 1995-1996 time period.

3.3 Summary

It appears that within locations, the level of recruitment is subject to significant year-to-year variation, while the amount of growth per oyster may be quite stable. The method of examining the growth of oysters in their second year after settlement, as pictured in Figures 3.3 to 3.7 is crude, but the use of a smoothing technique in future analyses could provide useful results.

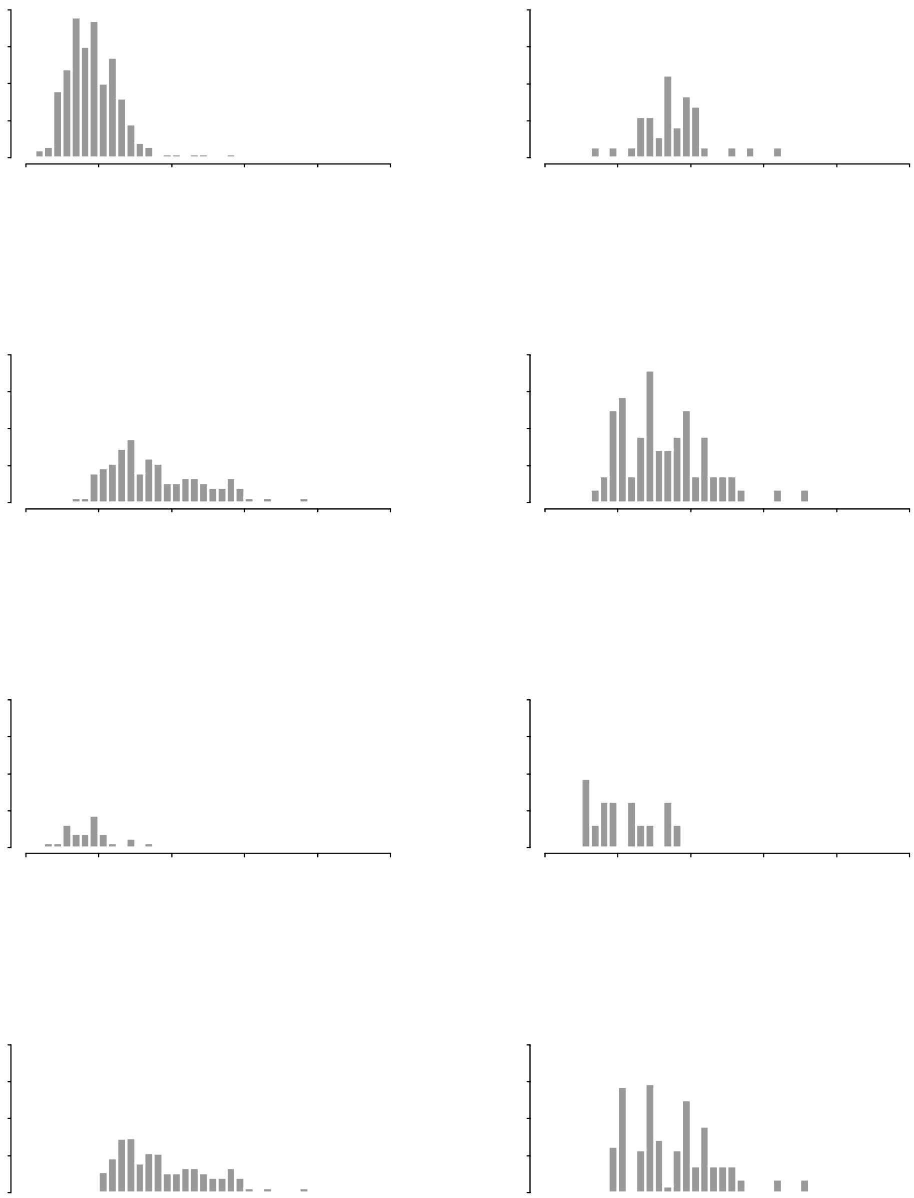

Figure 3.3: Oyster growth for the Harwood and Hernando locations. The height of the bars indicate average number of oysters per shell in that length interval. From top to bottom, the graphs show year one growth 94-95, years one and two growth 94-96, year one growth 95-96, and imputed year two growth 95-96.

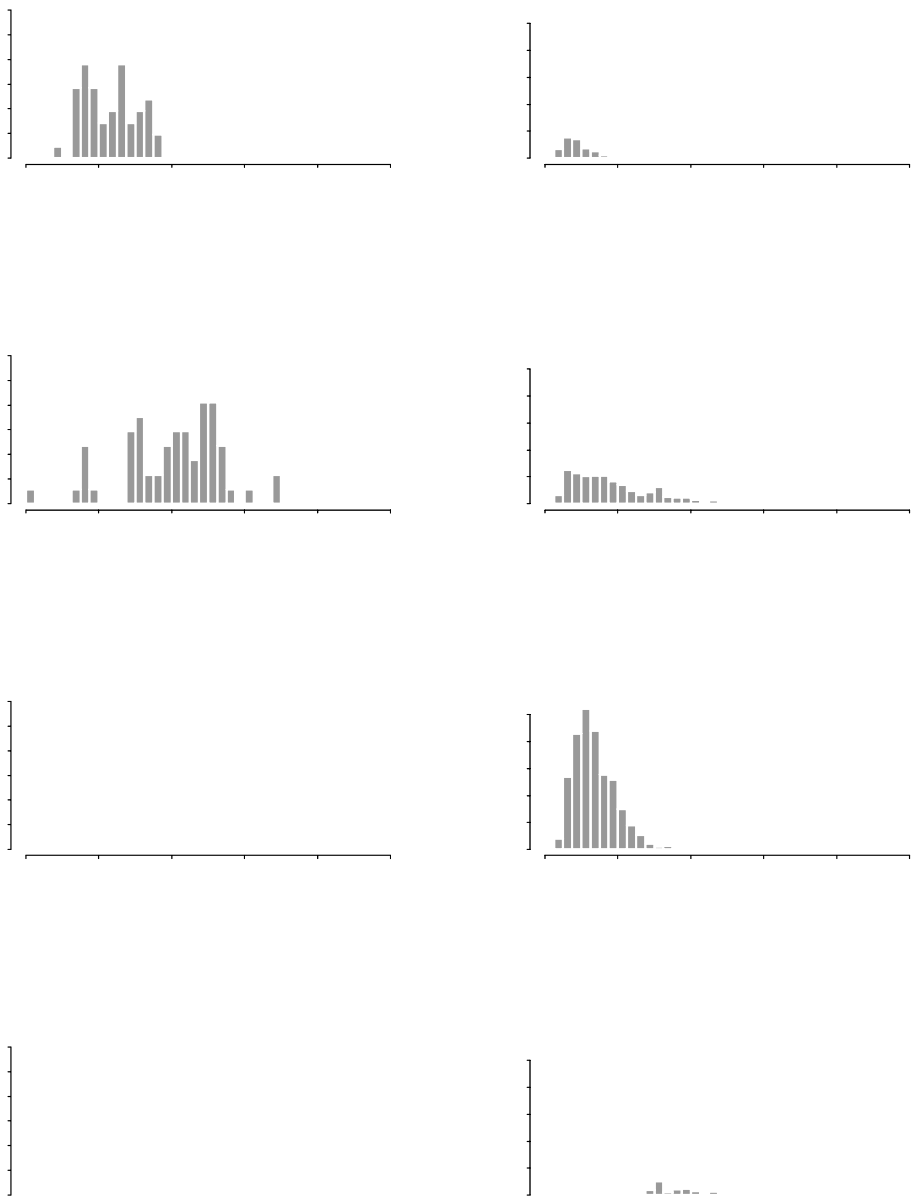

Figure 3.4: Oyster growth for the Lloyd and Pendrell locations. The height of the bars indicate average number of oysters per shell in that length interval. From top to bottom, the graphs show year one growth 94-95, years one and two growth 94-96, year one growth 95-96, and imputed year two growth 95-96.

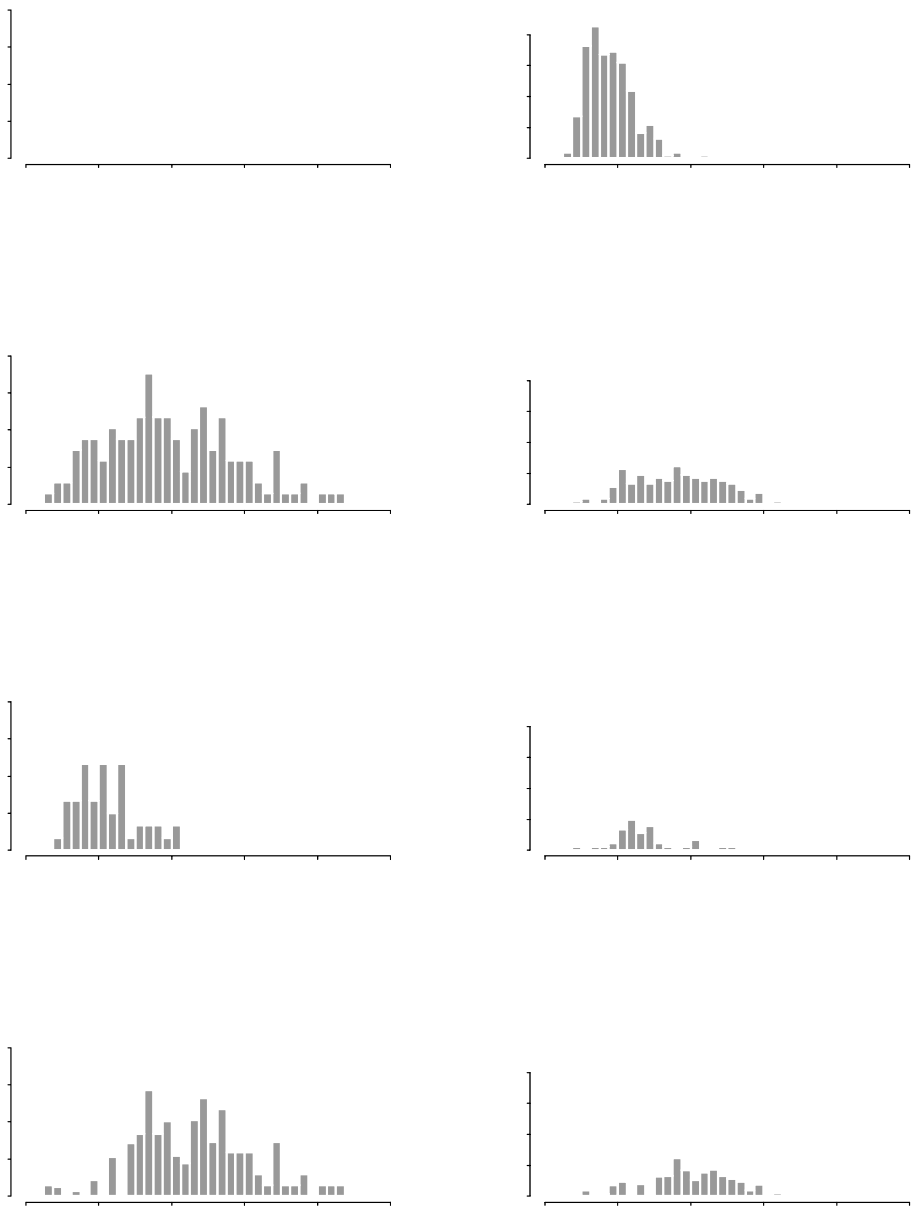

Figure 3.5: Oyster growth for the Savary and Sliammon locations. The height of the bars indicate average number of oysters per shell in that length interval. From top to bottom, the graphs show year one growth 94-95, years one and two growth 94-96, year one growth 95-96, and imputed year two growth 95-96.

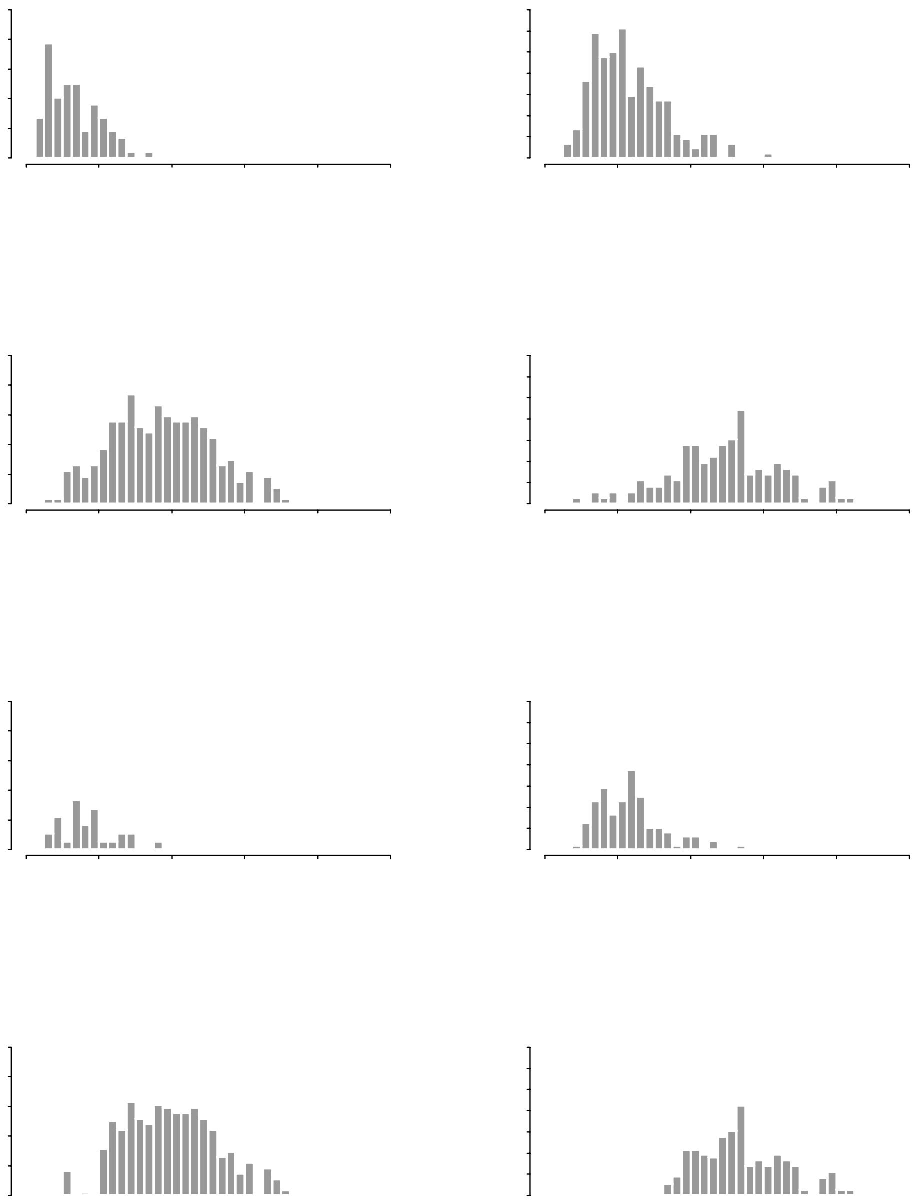

Figure 3.6: Oyster growth for the Squirrel and Stag locations. The height of the bars indicate average number of oysters per shell in that length interval. From top to bottom, the graphs show year one growth 94-95, years one and two growth 94-96, year one growth 95-96, and imputed year two growth 95-96.

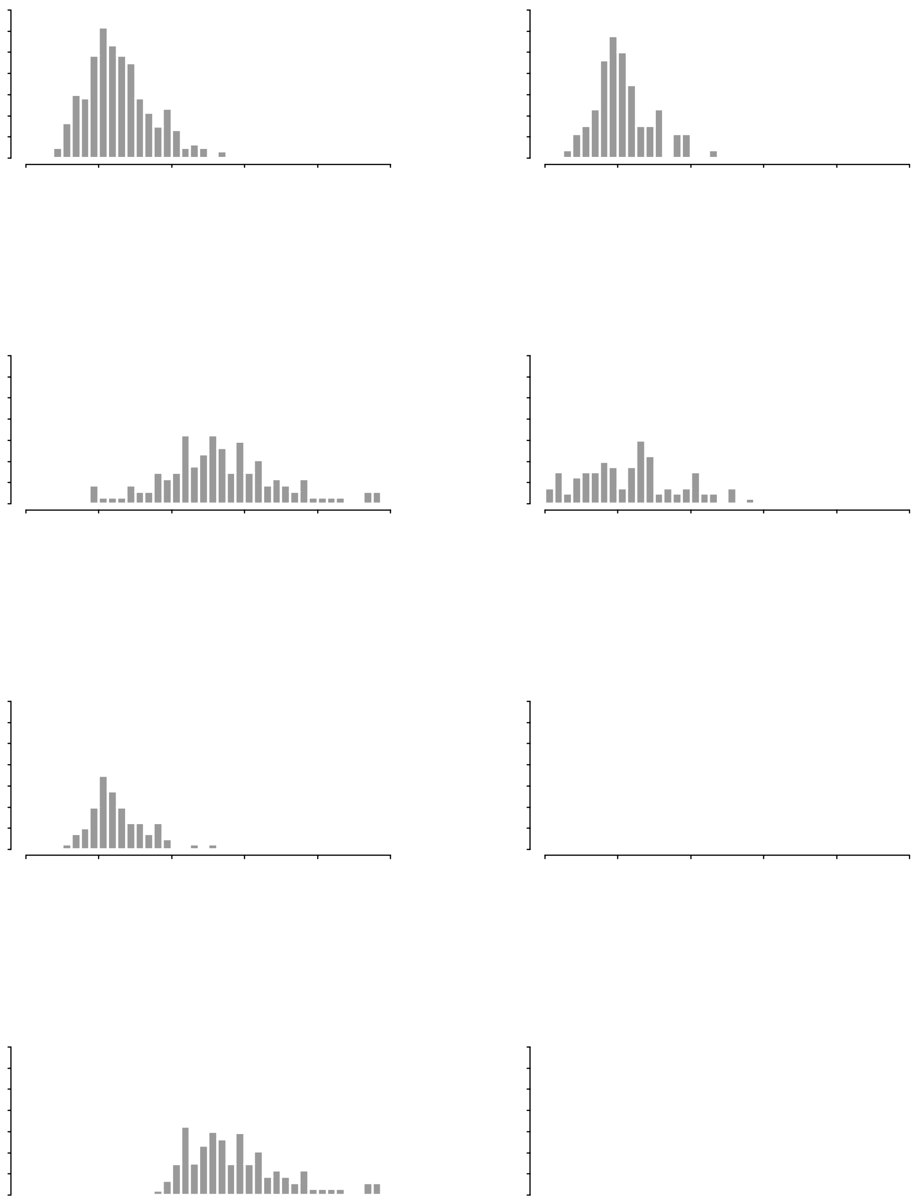

Figure 3.7: Oyster growth for the Sutil and Von Donop locations locations. The height of the bars indicate average number of oysters per shell in that length interval. From top to bottom, the graphs show year one growth 94-95, years one and two growth 94-96, year one growth 95-96, and imputed year two growth 95-96.

Chapter 4

Growth Data Analysis

As mentioned in the Introduction, this part of the study suffered from severe data problems. Two of the problems, missing bags and high mortality rates could possibly be overcome by assuming that the causes of the problems and the level of growth are unrelated. The increased abrasion issue however caused insurmountable problems in the data analysis.

Table 4.1 below shows a typical example of the growth data from one of the Vexar bags in a location – in this particular case bag number twenty three which was located at the Lloyd Point location. As can be seen in the rightmost column, many of the oysters showed a decrease in size from 1995 to 1996. Since these results do not in any way mirror what occurs in nature, this dataset was judged to be unusable.

Measurement (mm) in 1995	Measurement (mm) in 1996	Change in length (1996-1995)
76.8	79.0	2.2
117.4	114.8	-2.6
75.9	86.3	10.4
131.3	129.2	-2.1
140.5	138.4	-2.1
124.4	123.0	-1.4
93.6	97.5	3.9
95.3	102.3	7.0
96.7	99.8	3.1
109.7	107.9	-1.8
106.3	103.5	-2.8
141.8	137.2	-4.6

Table 4.1: Growth data from Vexar Bag #23, located at Lloyd Point .

Chapter 5

Discussion and Summary

This chapter will discuss the adequacy of the current methodology and suggest ways in which the methodology of the three different parts of the study could possibly be improved. It will also summarize the conclusions.

5.1 Density Survey

The first comment raises two concerns regarding the way the oyster beds are selected in the current design. The first concern is that the selection of only one oyster bed in each location allows no calculation of between bed variability since the between bed and between location variability are completely confounded with each other. The second concern is that the lack of randomization in the selection allows no estimation of the average density in each location (as opposed to the average density of a particular oyster bed in each location). If such estimates were desired then a multi-stage stratified sampling design such as one described in Gillespie and Kronlund (1999), involving cataloguing oyster habitat in each location, might be suggested.

The second comment is that systematic sampling appears to be a good idea. Cochran (1977) shows that the systematic random sample is much more effective than the simple random sample in the presence of a linear trend. The densities of oysters within the beds do not follow a linear trend since examination of the plots in Figures A.1.1.a to A.1.1.e in Appendix I (standardized residuals versus traverse) show that in some locations, non-linear trends may be present. However, since there is a lack of consistency to these trends, even within the same location, it would be impractical to include them in the models.

The third issue regarding the density study is whether there is a more efficient way of allocating our sampling effort within each bed. In other words, would the estimates increase in efficiency if we sampled more (or less) quadrats within each traverse point (along the same width line), accompanied by a decrease (or increase) in the number of traverse points. If we assume that the current design is reasonably close to a two-stage SRS design in which randomization is used in the selection of first-stage units (traverse points in this case) as well as in the selection of second stage units (width points), the following method outlined in Cochran (1977) provides a useful approach.

To optimize the allocation of sampling effort, the total cost (time in this case) is partitioned into two components: c_1n which is proportional to the number of primary units (traverse points) in the sample, and c_2nm which is proportional to the total number of second-stage units (quadrats) in the sample. The total cost can then be written

$$C = c_1n + c_2nm \qquad (5.1)$$

This can be used to minimize cost for a fixed variability, or equivalently to minimize variability for fixed cost. The optimum value of m is found to be

$$m_{opt} = \frac{S_2}{\sqrt{S_1^2 - S_2^2/M}}\sqrt{c_1/c_2} \qquad (5.2)$$

Where S_1^2 and S_2^2 represent variance among primary unit means, and among sub-units within primary units respectively (σ_T^2 and σ_ε^2 in earlier notation). If cost per primary unit is expressed as a proportion of cost per second-stage unit ($c_1 = ac_2$) and variance among primary unit as a proportion of variance among sub-units ($S_1^2 = bS_2^2$), then the expression for the optimum value of m is simplified to

$$m_{opt} = \frac{\sqrt{a}}{\sqrt{b - 1/M}} \tag{5.3}$$

Values for the proportion of variance, b, can be gathered from Table 2.1, and range from 0.13 to 0.19 depending upon the size class. Upon discussions with the fisheries coordinator for this study, the value 0.20 was provided as a rough estimate for the value of a. In nearly all the locations, the value of M was fixed at 20. Using these values, the value of m_{opt} ranges from 1.58 to 1.20. This implies that to reach the optimum, only one or two quadrats should be sampled within each traverse point, as opposed to from three to six in the current design.

5.2 Recruitment Survey

The same procedure regarding finding an optimal allocation of sampling effort that was used in the previous section can be applied for the recruitment survey. In this particular case, the primary units are bags and the secondary units are shells, and the problem to solve is to find an optimum number of shells per bag for a fixed cost. The values of the constants a, b, and M are determined to by the same method as earlier. The fisheries coordinator provided a ballpark figure for a of 2. By examining the model results, the value of b is estimated at .34. The most common value for M in the study was also found to be 12. Using these values and equation 5.3, the value of m_{opt} is found to be 2.8. Therefore the optimum number of shells in each bag on which to count oysters is three, which is just less than the current value of m of four.

Other suggestions for further study within the recruitment part of the survey include applying kernel density estimation techniques towards estimating the second year growth as was crudely done in Figures 3.3 to 3.7, and including a fourth year to allow comparision of two sets of data for growth over two years.

5.3 Growth Survey

A challenging problem still exists in designing a survey to estimate growth of individual oysters. One suggestion might be to measure the growth of cultured oysters which are grown for consumption in trays, although these optimum conditions would not really be comparable to the conditions faced by oysters growing under natural conditions.

5.4 Summary

The results of Chapter two indicate that there may be some support for the idea that removal, by harvesting for example, may encourage settlement of new spat. In Chapter three, it was found that although the level of recruitment may be quite variable, the level of growth, at least for oysters in their first year, seems somewhat stable. The presentation of the preliminary results of the growth study in Chapter four showed that the data are unusable. This chapter included a discussion of improvements to the protocol, and suggestions for further analysis.

Appendix I

Residual Plots

This appendix contains two sets of residual plots. Both sets of graphs are based upon fitting a mixed-effects model using logarithmically transformed data and use standardized residuals. For the first set of residual plots, the residuals are plotted against the traverse point and for the second set, the residuals are plotted against the width point. Since each individual graph shows a set of residuals for one particular location by size class by year combination, each location will have fifteen individual graphs for each set of plots.

The reason for constructing these plots is to permit identification of correlations between the residuals and other variables. If a correlation is recognized, then an addition to the model of a factor may be called for. The following sets of plots all have a smooth loess line superimposed over the residual points. The purpose of this line is to allow identification of trends when doing so by eye is difficult – when there are many tightly clustered points for example. Additionally, since the data is discrete and there will typically be many observations in each year by size by location combination with the same value, to allow the viewer to see large clusters of data, the points have been jittered. It is apparent that some trends are present – Sliammon Beach 1996, size class 1 in Figure A.1.1.c shows a clear upward trend of the residuals against traverse points, and many of the plots for Squirrel Cove Bay in Figure A.1.2.d show a hump of higher residuals against width point.

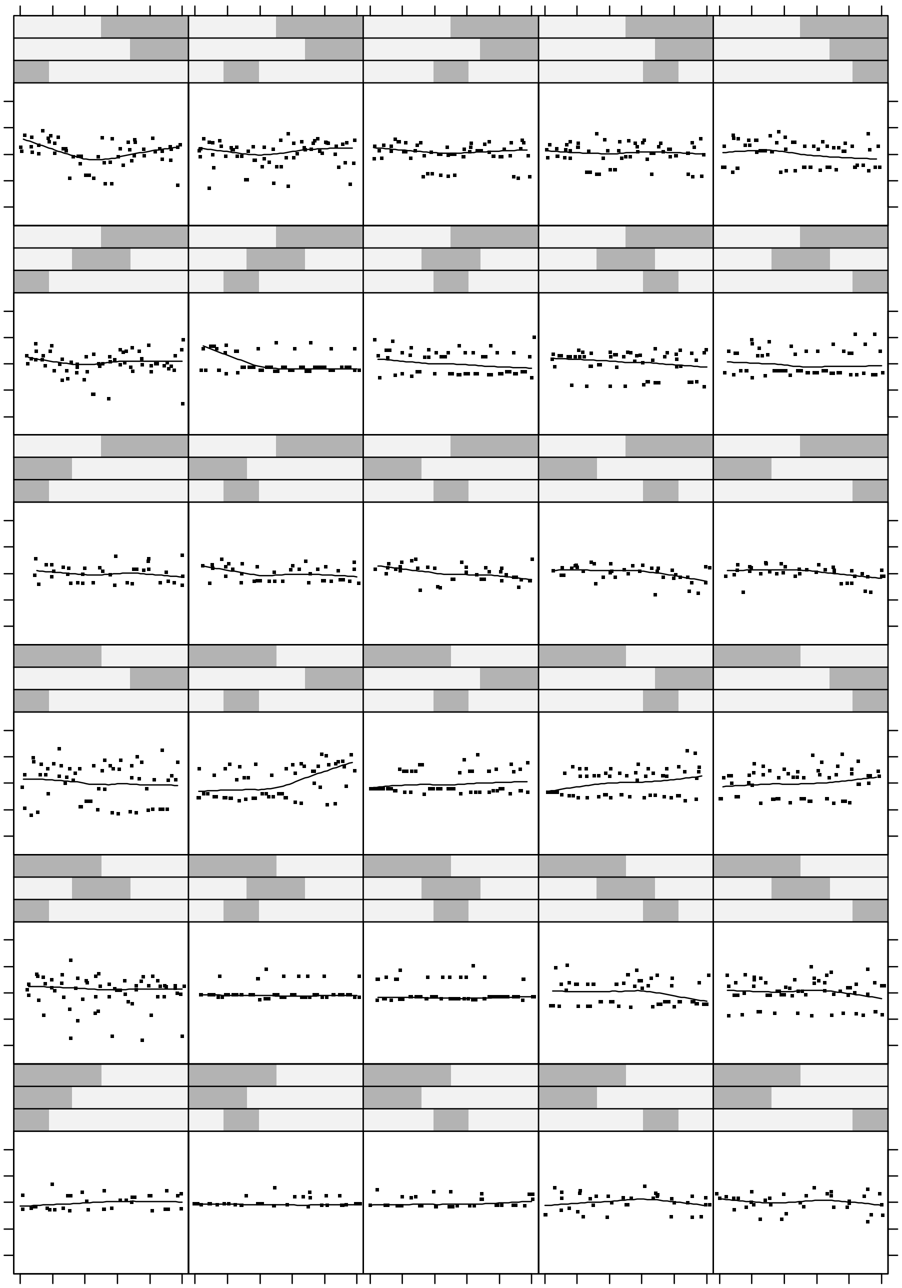

Figure A.1.1.a: Plot of residuals resulting from the mixed effects model against traverse for the Harwood and Hernando locations. Each row shows size classes 1-5 for a single year.

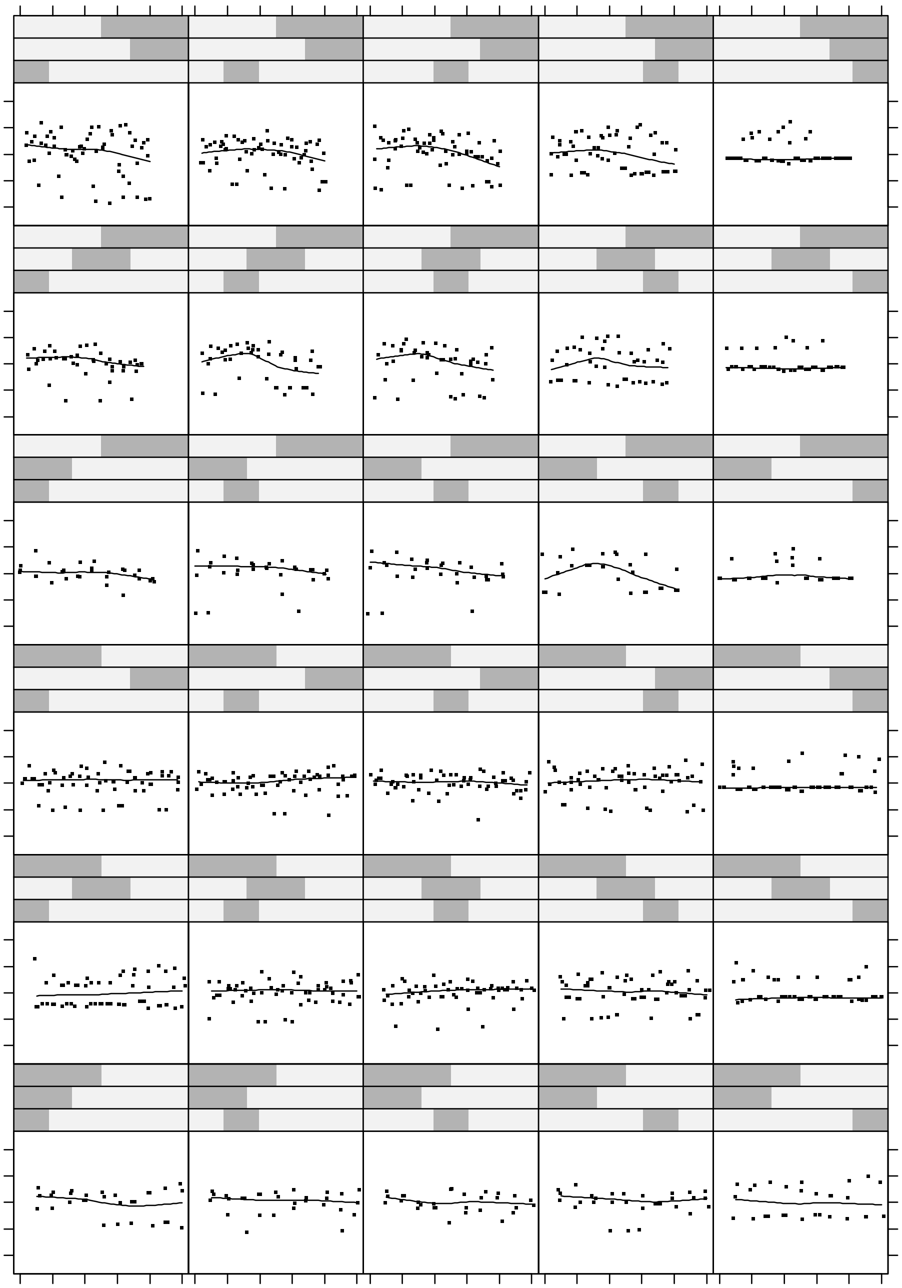

Figure A.1.1.b: Plot of residuals resulting from the mixed effects model against traverse for the Lloyd and Pendrell locations. Each row shows size classes 1-5 for a single year.

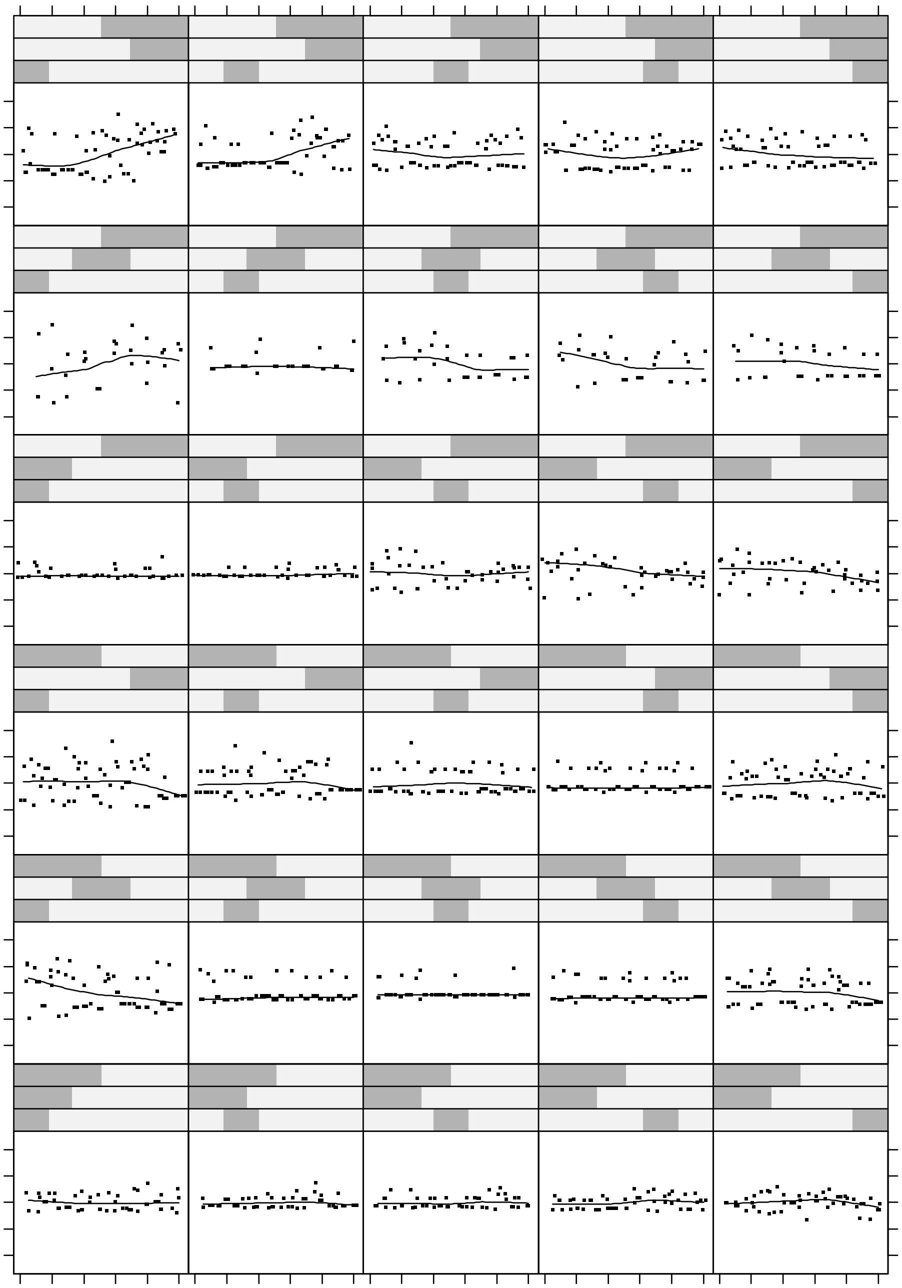

Figure A.1.1.c: Plot of residuals resulting from the mixed effects model against traverse for the Savary and Sliammon locations. Each row shows size classes 1-5 for a single year.

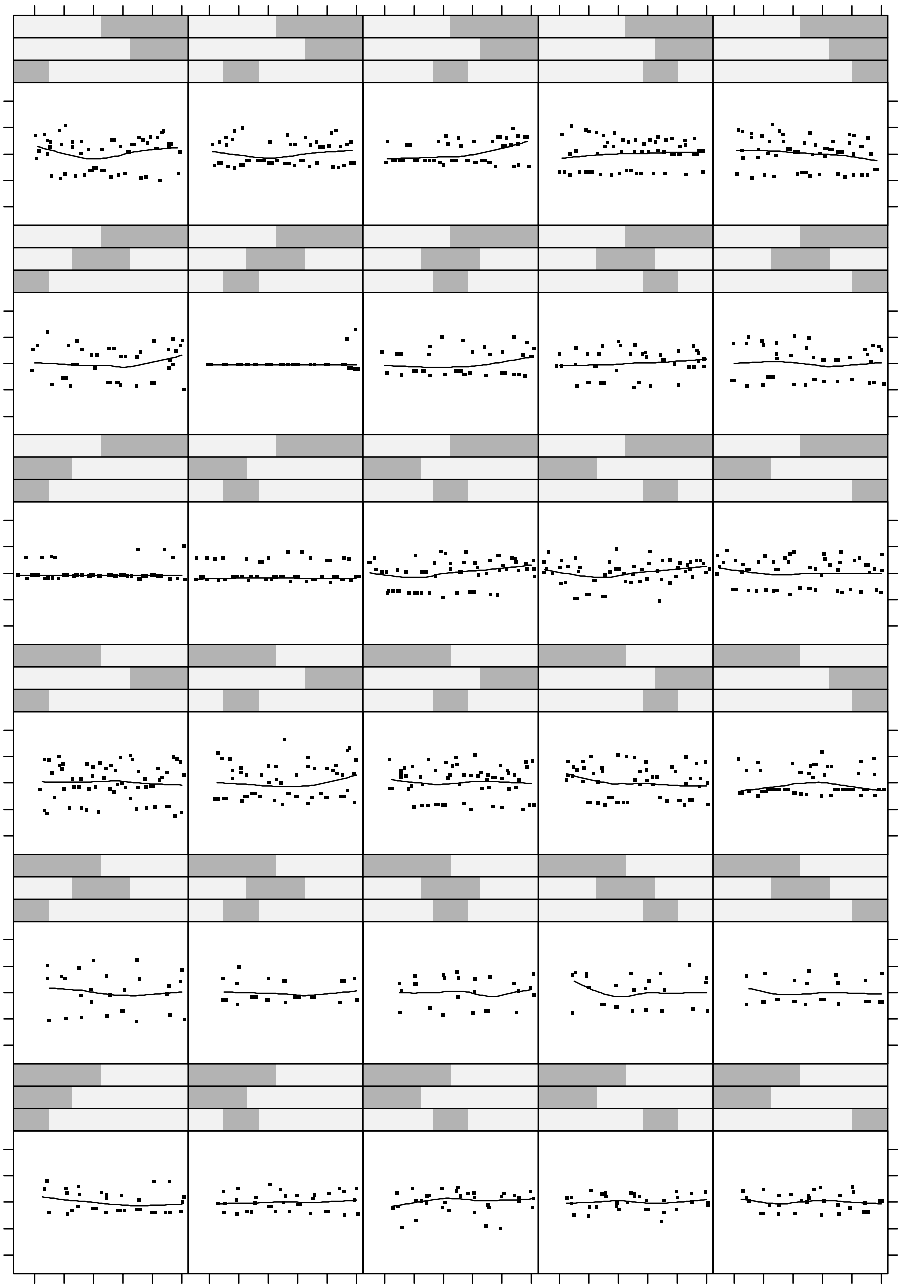

Figure A.1.1.d: Plot of residuals resulting from the mixed effects model against traverse for the Squirrel and Stag locations. Each row shows size classes 1-5 for a single year.

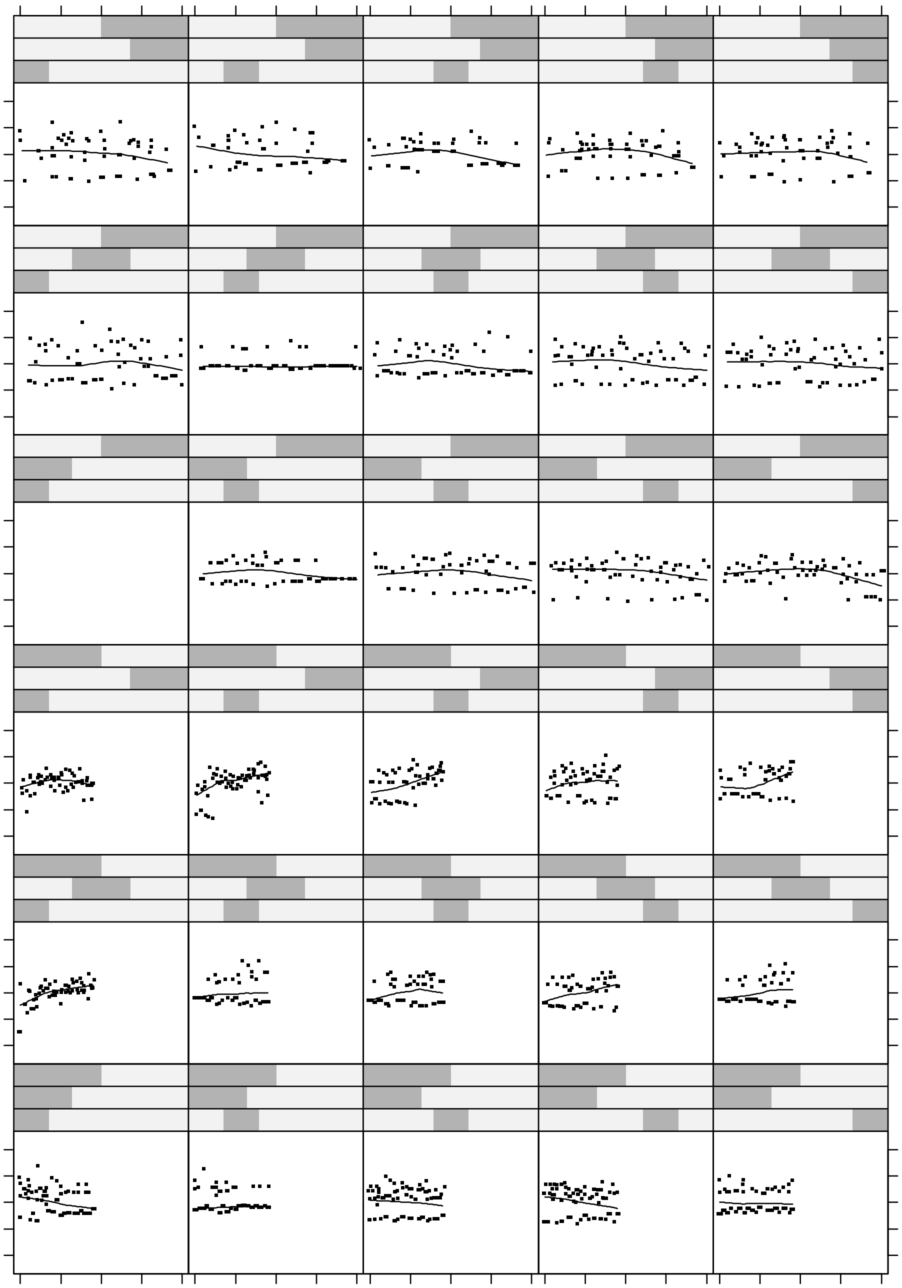

Figure A.1.1.e: Plot of residuals resulting from the mixed effects model against traverse for the Sutil and Von Donop locations. Each row shows size classes 1-5 for a single year.

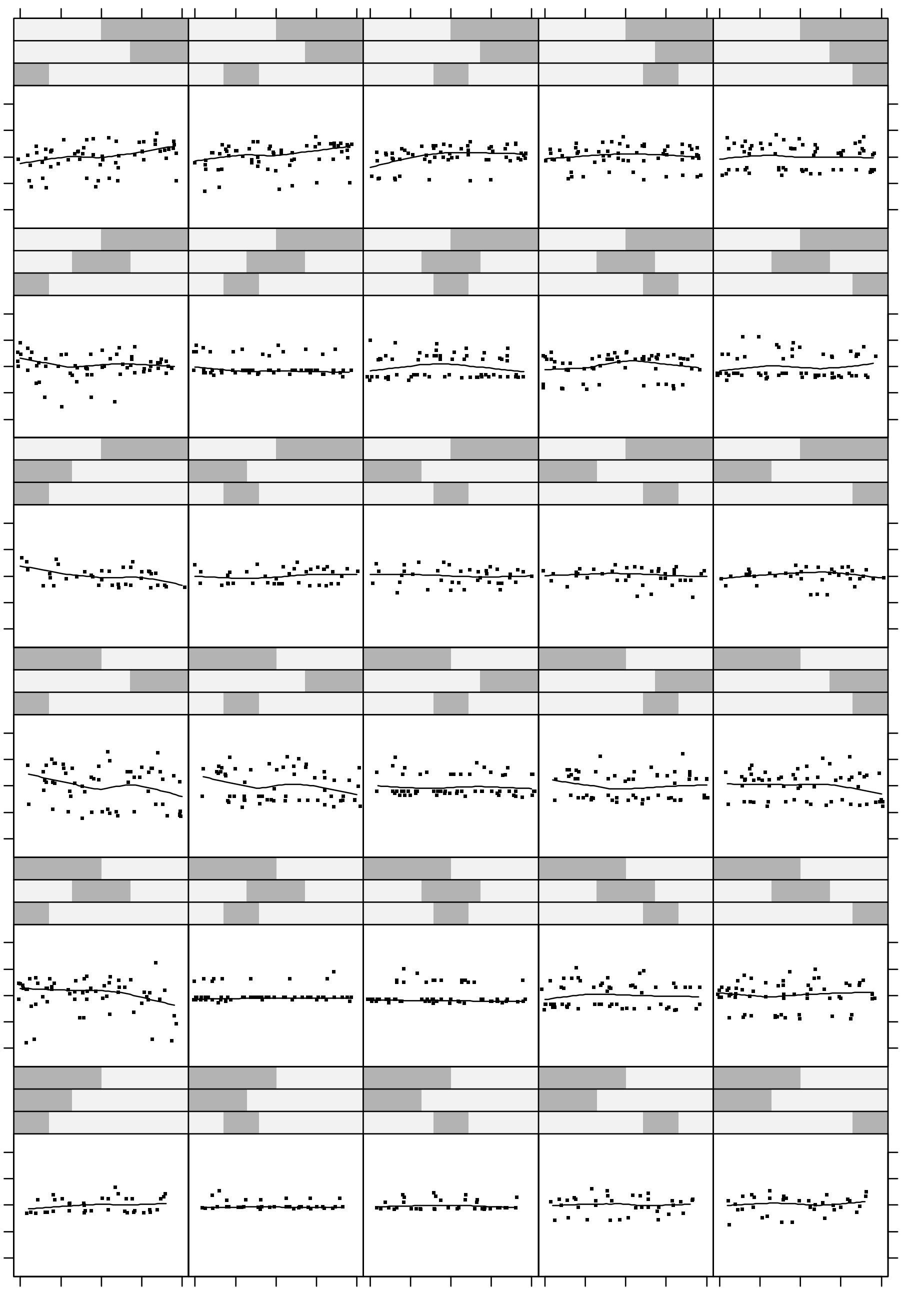

Figure A.1.2.a: Plot of residuals resulting from the mixed effects model against width point for the Harwood and Hernando locations. Each row shows size classes 1-5 for a single year.

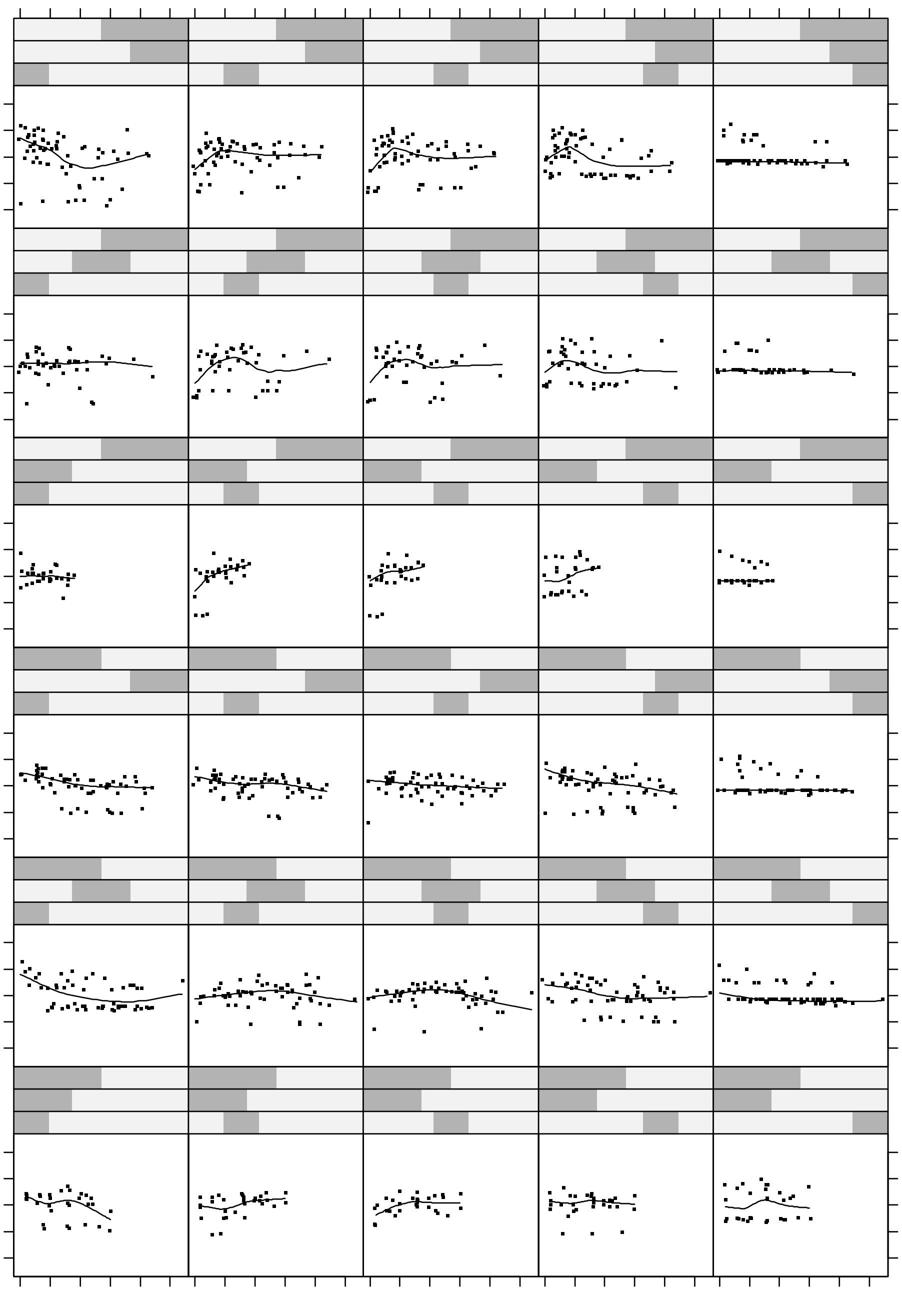

Figure A.1.2.b: Plot of residuals resulting from the mixed effects model against width point for the Lloyd and Pendrell locations. Each row shows size classes 1-5 for a single year.

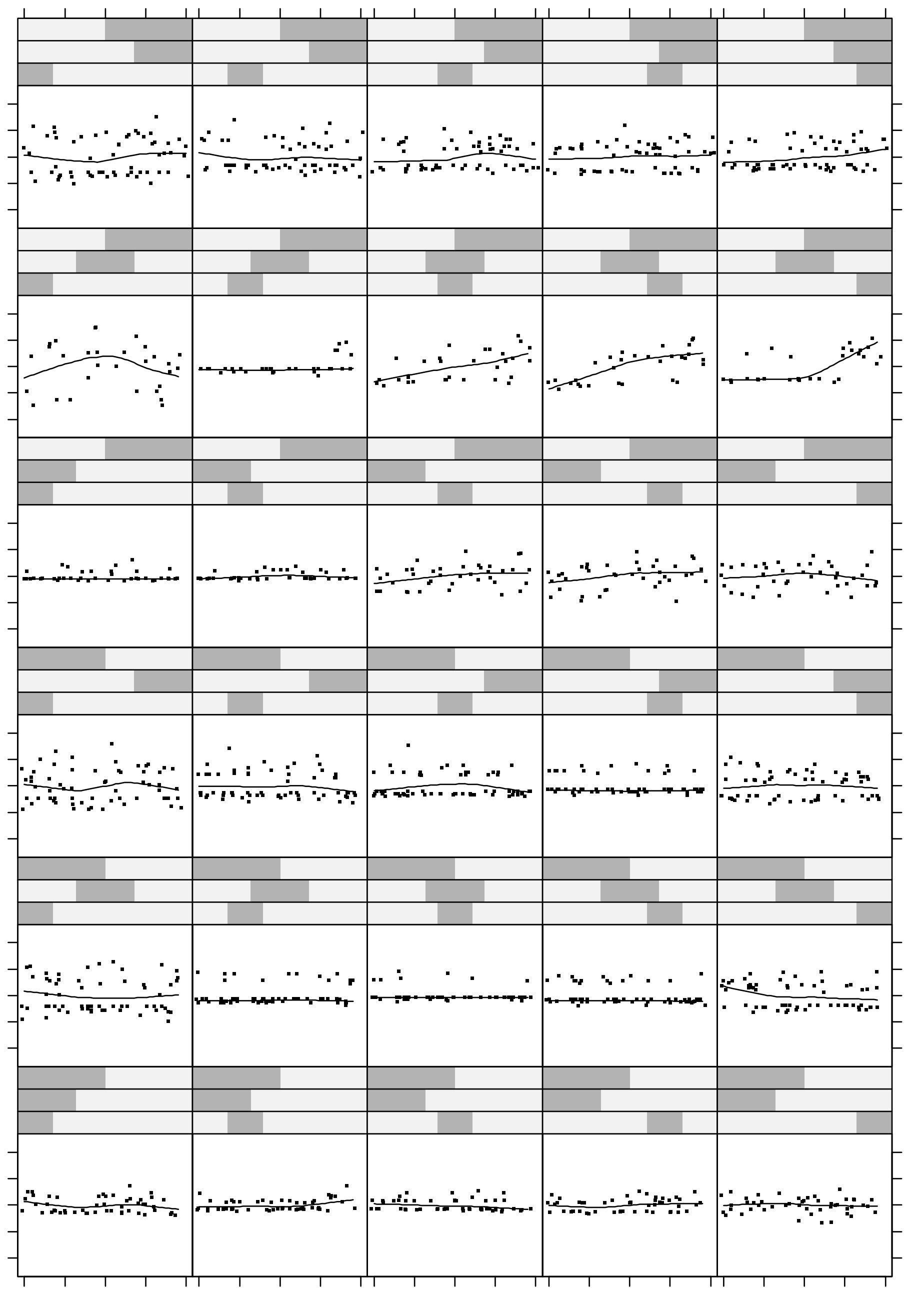

Figure A.1.2.c: Plot of residuals resulting from the mixed effects model against width point for the Savary and Sliammon locations. Each row shows size classes 1-5 for a single year.

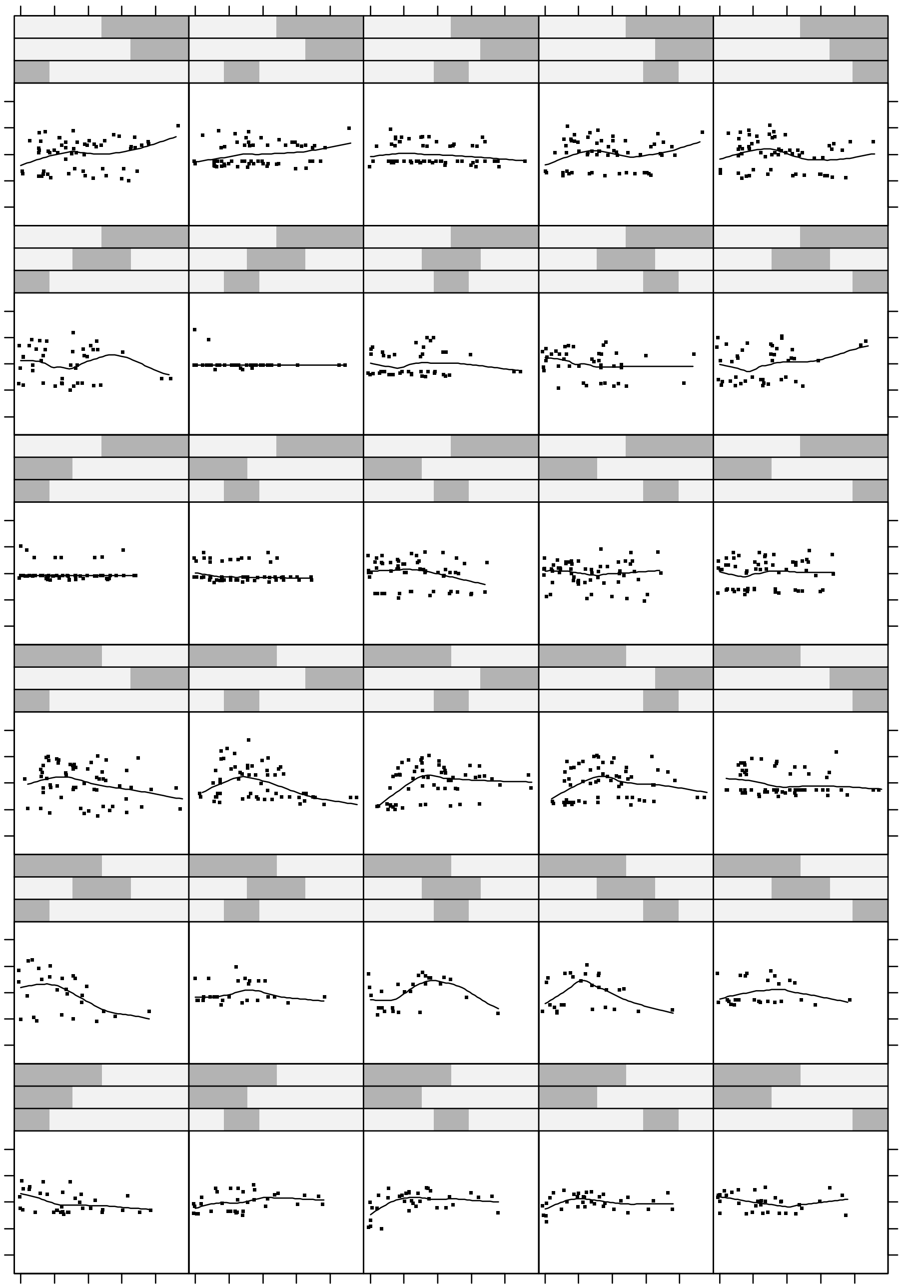

Figure A.1.2.d: Plot of residuals resulting from the mixed effects model against width point for the Squirrel and Stag locations. Each row shows size classes 1-5 for a single year.

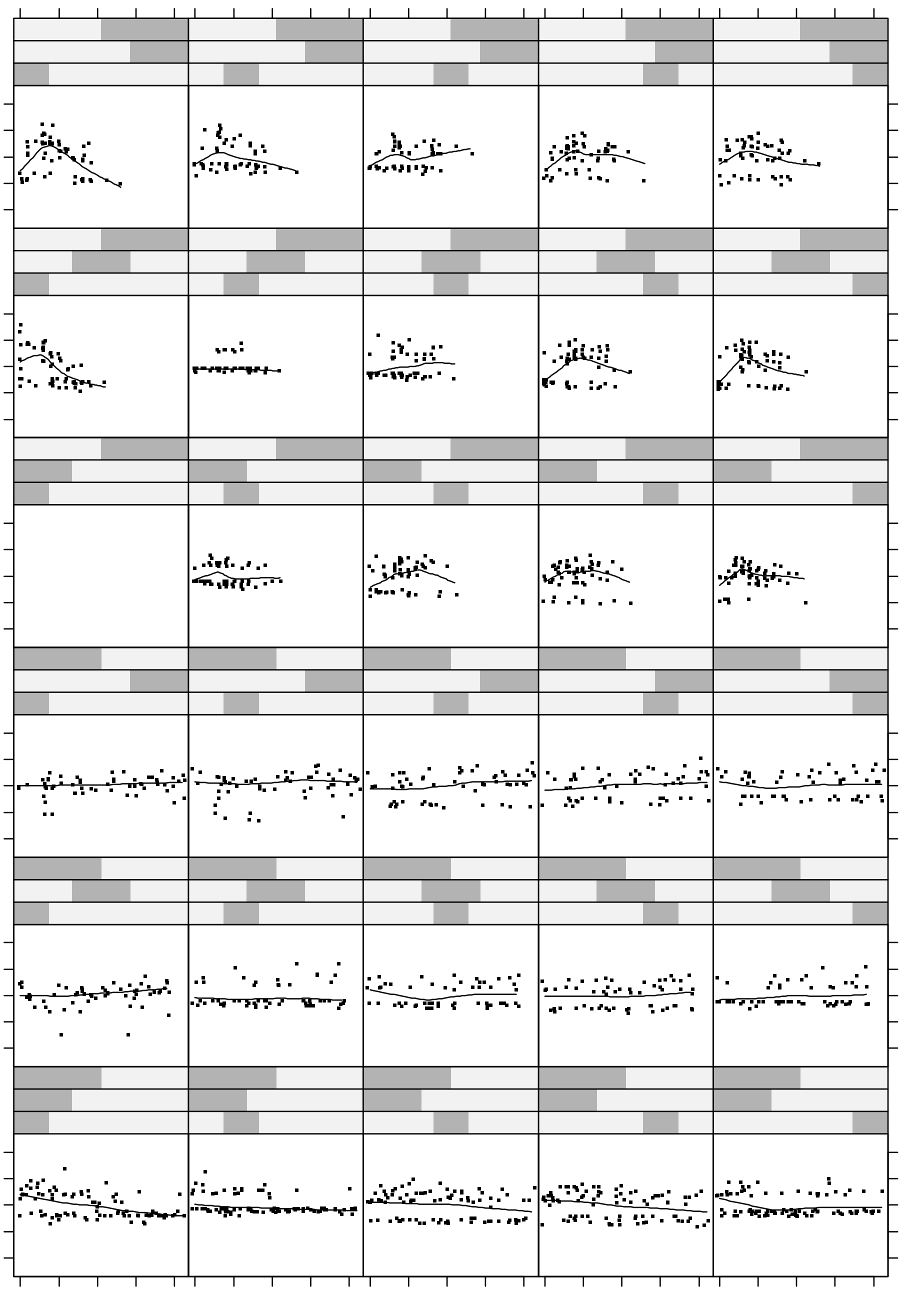

Figure A.1.2.e: Plot of residuals resulting from the mixed effects model against width point for the Sutil and Von Donop locations. Each row shows size classes 1-5 for a single year.

Appendix II

Numerical Density Results

This appendix consists of two tables – one for estimates of numerical density, and one for p-values of differences.

A.2.1 Numerical density estimates

Table A.2.1 below lists estimates of mean density for all size by year by location combinations based on the mixed effects model fitted to logarithmically transformed data. The point estimates and the upper and lower boundaries of the 95% confidence intervals for the median density have all been back-transformed, while the estimated standard error is in the logarithmic scale.

Table A.2.1: Estimates and confidence intervals of numerical density per square metre.

Location	Year	Size	Median	SE	Lower	Upper
Harwood	94	1	0.67	0.24	0.03	1.69
Harwood	94	2	0.20	0.19	-0.17	0.74
Harwood	94	3	0.36	0.19	-0.06	0.95
Harwood	94	4	2.45	0.20	1.31	4.14
Harwood	94	5	7.84	0.19	5.08	11.84
Harwood	95	1	48.00	0.20	32.39	70.92
Harwood	95	2	0.29	0.15	-0.04	0.73
Harwood	95	3	0.53	0.15	0.15	1.05
Harwood	95	4	1.64	0.16	0.92	2.62
Harwood	95	5	4.63	0.15	3.19	6.58

Table A.2.1 continued

Location	Year	Size	Median	SE	Lower	Upper
Harwood	96	1	8.36	0.20	5.36	12.76
Harwood	96	2	2.72	0.15	1.76	4.02
Harwood	96	3	0.82	0.15	0.36	1.43
Harwood	96	4	1.88	0.16	1.09	2.96
Harwood	96	5	3.41	0.15	2.27	4.95
Hernando	94	1	1.28	0.24	0.43	2.64
Hernando	94	2	0.98	0.18	0.39	1.82
Hernando	94	3	2.43	0.18	1.41	3.87
Hernando	94	4	4.78	0.20	2.94	7.49
Hernando	94	5	3.98	0.18	2.47	6.13
Hernando	95	1	20.27	0.20	13.49	30.22
Hernando	95	2	0.62	0.15	0.20	1.17
Hernando	95	3	1.39	0.15	0.79	2.19
Hernando	95	4	4.61	0.16	3.08	6.71
Hernando	95	5	1.07	0.15	0.54	1.79
Hernando	96	1	12.03	0.20	7.88	18.13
Hernando	96	2	13.84	0.15	10.04	18.95
Hernando	96	3	5.34	0.15	3.75	7.47
Hernando	96	4	4.86	0.16	3.26	7.06
Hernando	96	5	2.35	0.15	1.49	3.51
Lloyd	94	1	5.28	0.28	2.65	9.80
Lloyd	94	2	12.13	0.21	7.64	18.96
Lloyd	94	3	20.74	0.21	13.44	31.74
Lloyd	94	4	10.04	0.23	6.04	16.31
Lloyd	94	5	2.07	0.21	1.01	3.67
Lloyd	95	1	1.68	0.20	0.81	2.97
Lloyd	95	2	9.16	0.15	6.50	12.76
Lloyd	95	3	16.98	0.15	12.36	23.20
Lloyd	95	4	6.38	0.17	4.33	9.24
Lloyd	95	5	0.56	0.16	0.15	1.12
Lloyd	96	1	7.40	0.20	4.72	11.32
Lloyd	96	2	12.31	0.15	8.90	16.90
Lloyd	96	3	19.78	0.15	14.55	26.76
Lloyd	96	4	7.69	0.16	5.32	10.95
Lloyd	96	5	0.58	0.15	0.18	1.13
Pendrell	94	1	108.05	0.28	61.97	187.87
Pendrell	94	2	26.00	0.22	16.67	40.25
Pendrell	94	3	24.21	0.21	15.65	37.18
Pendrell	94	4	4.11	0.23	2.24	7.06
Pendrell	94	5	0.60	0.22	0.04	1.44
Pendrell	95	1	23.86	0.23	14.92	37.81
Pendrell	95	2	11.44	0.17	7.82	16.55
Pendrell	95	3	15.37	0.17	10.67	21.96
Pendrell	95	4	3.57	0.19	2.15	5.62
Pendrell	95	5	0.43	0.18	0.01	1.03
Pendrell	96	1	44.96	0.20	30.32	66.46
Pendrell	96	2	17.55	0.15	12.80	23.94

Table A.2.1 continued

Location	Year	Size	Median	SE	Lower	Upper
Pendrell	96	3	14.34	0.15	10.49	19.50
Pendrell	96	4	4.02	0.16	2.65	5.90
Pendrell	96	4	4.02	0.16	2.65	5.90
Pendrell	96	5	0.54	0.15	0.14	1.07
Savary	94	1	0.83	0.21	0.21	1.75
Savary	94	2	0.47	0.16	0.07	1.01
Savary	94	3	0.42	0.16	0.04	0.94
Savary	94	4	0.78	0.17	0.26	1.50
Savary	94	5	3.09	0.16	1.97	4.62
Savary	95	1	2.76	0.20	1.56	4.53
Savary	95	2	0.51	0.15	0.13	1.04
Savary	95	3	0.23	0.15	-0.08	0.64
Savary	95	4	0.57	0.16	0.14	1.16
Savary	95	5	1.85	0.15	1.12	2.84
Savary	96	1	3.64	0.19	2.19	5.75
Savary	96	2	1.31	0.15	0.73	2.08
Savary	96	3	0.86	0.14	0.40	1.46
Savary	96	4	0.52	0.16	0.12	1.08
Savary	96	5	2.00	0.15	1.24	3.01
Sliammon	94	1	0.27	0.23	-0.19	0.98
Sliammon	94	2	0.22	0.18	-0.14	0.72
Sliammon	94	3	2.54	0.17	1.51	3.98
Sliammon	94	4	5.50	0.19	3.45	8.49
Sliammon	94	5	3.64	0.18	2.27	5.59
Sliammon	95	1	19.38	0.28	10.84	34.06
Sliammon	95	2	0.38	0.21	-0.09	1.09
Sliammon	95	3	2.24	0.21	1.15	3.87
Sliammon	95	4	3.62	0.23	1.95	6.25
Sliammon	95	5	1.85	0.21	0.87	3.34
Sliammon	96	1	5.30	0.20	3.29	8.27
Sliammon	96	2	1.90	0.15	1.15	2.91
Sliammon	96	3	1.57	0.15	0.92	2.43
Sliammon	96	4	2.46	0.16	1.51	3.76
Sliammon	96	5	1.42	0.15	0.79	2.26
Squirrel	94	1	1.08	0.25	0.26	2.43
Squirrel	94	2	1.35	0.20	0.59	2.45
Squirrel	94	3	7.48	0.19	4.80	11.39
Squirrel	94	4	5.21	0.21	3.10	8.41
Squirrel	94	5	1.67	0.20	0.81	2.94
Squirrel	95	1	5.97	0.29	2.93	11.34
Squirrel	95	2	0.79	0.22	0.15	1.78
Squirrel	95	3	4.06	0.22	2.28	6.79
Squirrel	95	4	2.90	0.24	1.43	5.27
Squirrel	95	5	1.10	0.23	0.35	2.26
Squirrel	96	1	8.84	0.20	5.70	13.44
Squirrel	96	2	2.73	0.15	1.78	4.02
Squirrel	96	3	5.88	0.15	4.15	8.20

Table A.2.1 continued

Location	Year	Size	Median	SE	Lower	Upper
Squirrel	96	4	4.18	0.16	2.77	6.12
Squirrel	96	5	1.11	0.15	0.57	1.84
Stag	94	1	0.30	0.19	-0.11	0.90
Stag	94	2	0.56	0.15	0.16	1.09
Stag	94	3	4.58	0.15	3.18	6.44
Stag	94	4	9.35	0.16	6.54	13.20
Stag	94	5	3.19	0.15	2.11	4.63
Stag	95	1	4.85	0.23	2.70	8.25
Stag	95	2	0.13	0.18	-0.20	0.61
Stag	95	3	1.22	0.18	0.57	2.14
Stag	95	4	4.87	0.19	3.01	7.59
Stag	95	5	3.27	0.18	1.99	5.08
Stag	96	1	4.63	0.20	2.83	7.26
Stag	96	2	1.20	0.15	0.63	1.95
Stag	96	3	1.05	0.15	0.53	1.73
Stag	96	4	3.72	0.16	2.43	5.49
Stag	96	5	4.41	0.15	3.02	6.27
Sutil	94	1	1.70	0.18	0.90	2.84
Sutil	94	2	0.56	0.14	0.19	1.05
Sutil	94	3	2.73	0.13	1.88	3.85
Sutil	94	4	2.97	0.15	1.97	4.30
Sutil	94	5	0.87	0.14	0.43	1.45
Sutil	95	1	51.51	0.20	34.42	76.84
Sutil	95	2	0.87	0.15	0.38	1.53
Sutil	95	3	1.31	0.15	0.72	2.11
Sutil	95	4	2.21	0.17	1.32	3.45
Sutil	95	5	0.98	0.16	0.46	1.68
Sutil	96	1	21.62	0.20	14.26	32.54
Sutil	96	2	18.84	0.15	13.64	25.88
Sutil	96	3	4.16	0.15	2.83	5.95
Sutil	96	4	3.19	0.17	2.03	4.81
Sutil	96	5	2.18	0.16	1.34	3.31
Von Donop	94	2	0.84	0.15	0.37	1.47
Von Donop	94	3	3.14	0.15	2.10	4.53
Von Donop	94	4	7.19	0.16	4.96	10.26
Von Donop	94	5	8.35	0.15	5.95	11.58
Von Donop	95	1	3.10	0.19	1.80	5.00
Von Donop	95	2	0.28	0.15	-0.05	0.71
Von Donop	95	3	1.14	0.15	0.60	1.85
Von Donop	95	4	3.48	0.16	2.26	5.15
Von Donop	95	5	4.28	0.15	2.93	6.09
Von Donop	96	1	5.48	0.22	3.22	8.96
Von Donop	96	2	1.37	0.17	0.70	2.30
Von Donop	96	3	1.86	0.16	1.08	2.94
Von Donop	96	4	4.17	0.18	2.63	6.36
Von Donop	96	5	5.54	0.17	3.71	8.09

A.2.2 Density differences between years

Table A.2.2 below lists p-values for the null hypothesis that there is no difference between years in density in the same location and size class. No adjustment has been made for multiple comparisions.

Table A.2.2: P-values for differences in numerical density per square metre.

Size	Location	Year	Vs_Year	P-value
1	Harwood	94	95	0.0001
1	Harwood	95	96	0.0001
2	Harwood	94	95	0.7804
2	Harwood	95	96	0.0001
3	Harwood	94	95	0.6023
3	Harwood	95	96	0.4200
4	Harwood	94	95	0.3030
4	Harwood	95	96	0.7036
5	Harwood	94	95	0.0642
5	Harwood	95	96	0.2539
1	Hernando	94	95	0.0001
1	Hernando	95	96	0.0767
2	Hernando	94	95	0.3872
2	Hernando	95	96	0.0001
3	Hernando	94	95	0.1187
3	Hernando	95	96	0.0001
4	Hernando	94	95	0.9031
4	Hernando	95	96	0.8460
5	Hernando	94	95	0.0003
5	Hernando	95	96	0.0254
1	Lloyd	94	95	0.0128
1	Lloyd	95	96	0.0001
2	Lloyd	94	95	0.3303
2	Lloyd	95	96	0.2110
3	Lloyd	94	95	0.4608
3	Lloyd	95	96	0.4935
4	Lloyd	94	95	0.1559
4	Lloyd	95	96	0.4824
5	Lloyd	94	95	0.0111
5	Lloyd	95	96	0.9527
1	Pendrell	94	95	0.0001
1	Pendrell	95	96	0.0405
2	Pendrell	94	95	0.0055
2	Pendrell	95	96	0.0843

Table A.2.2 continued

Size	Location	Year	Vs_Year	P-value
3	Pendrell	94	95	0.1136
3	Pendrell	95	96	0.7759
4	Pendrell	94	95	0.7075
4	Pendrell	95	96	0.7062
5	Pendrell	94	95	0.6991
5	Pendrell	95	96	0.7638
1	Savary	94	95	0.0117
1	Savary	95	96	0.4446
2	Savary	94	95	0.8838
2	Savary	95	96	0.0461
3	Savary	94	95	0.4862
3	Savary	95	96	0.0439
4	Savary	94	95	0.6008
4	Savary	95	96	0.8969
5	Savary	94	95	0.1057
5	Savary	95	96	0.8128
1	Sliammon	94	95	0.0001
1	Sliammon	95	96	0.0006
2	Sliammon	94	95	0.6616
2	Sliammon	95	96	0.0046
3	Sliammon	94	95	0.7441
3	Sliammon	95	96	0.3637
4	Sliammon	94	95	0.2544
4	Sliammon	95	96	0.3020
5	Sliammon	94	95	0.0810
5	Sliammon	95	96	0.5293
1	Squirrel	94	95	0.0019
1	Squirrel	95	96	0.3252
2	Squirrel	94	95	0.3647
2	Squirrel	95	96	0.0067
3	Squirrel	94	95	0.0778
3	Squirrel	95	96	0.2437
4	Squirrel	94	95	0.1488
4	Squirrel	95	96	0.3315
5	Squirrel	94	95	0.4204
5	Squirrel	95	96	0.9782
1	Stag	94	95	0.0001
1	Stag	95	96	0.8984
2	Stag	94	95	0.1745
2	Stag	95	96	0.0050
3	Stag	94	95	0.0001
3	Stag	95	96	0.7229
4	Stag	94	95	0.0249
4	Stag	95	96	0.3870
5	Stag	94	95	0.9380
5	Stag	95	96	0.3150

Table A.2.2 continued

Size	Location	Year	Vs_Year	P-value
1	Sutil	94	95	0.0001
1	Sutil	95	96	0.0031
2	Sutil	94	95	0.3820
2	Sutil	95	96	0.0001
3	Sutil	94	95	0.0178
3	Sutil	95	96	0.0002
4	Sutil	94	95	0.3429
4	Sutil	95	96	0.2569
5	Sutil	94	95	0.7869
5	Sutil	95	96	0.0313
1	Von	94	95	0.9007
1	Von	95	96	0.1182
2	Von	94	95	0.0862
2	Von	95	96	0.0062
3	Von	94	95	0.0016
3	Von	95	96	0.1821
4	Von	94	95	0.0085
4	Von	95	96	0.5521
5	Von	94	95	0.0076
5	Von	95	96	0.3395

Appendix III

Weight Density Results

This appendix consists of two tables – one for estimates of weight density, and one for p-values of differences of weights in the same location, between consecutive years.

A.3.1 Weight density estimates

Table A.3.1 below lists estimates of mean density by weight in kilograms per square metre for all size by year by location combinations based on the mixed effects model fitted to logarithmically transformed data. The point estimates and the upper and lower boundaries of the 95% confidence intervals for the median density have all been back-transformed, while the estimated standard error is in the logarithmic scale.

Table A.3.1: Estimates and confidence intervals of median weight in kilograms per square metre.

Location	Year	Weight	Lower	Upper
Harwood	94	4.32	2.74	6.76
Harwood	95	2.56	1.75	3.69
Harwood	96	2.55	1.75	3.69
Hernando	94	2.95	1.88	4.56
Hernando	95	1.97	1.34	2.87
Hernando	96	3.43	2.37	4.92
Lloyd	94	4.83	2.89	7.97

Table A.3.1 continued

Location	Year	Weight	Lower	Upper
Lloyd	95	3.52	2.42	5.10
Lloyd	96	3.96	2.75	5.66
Pendrell	94	3.01	1.76	5.05
Pendrell	95	3.16	2.05	4.81
Pendrell	96	2.33	1.59	3.37
Savary	94	1.45	0.94	2.19
Savary	95	1.21	0.79	1.80
Savary	96	0.89	0.58	1.32
Sliammon	94	2.74	1.76	4.20
Sliammon	95	2.16	1.25	3.64
Sliammon	96	1.56	1.04	2.28
Squirrel	94	2.56	1.56	4.13
Squirrel	95	1.46	0.80	2.58
Squirrel	96	2.63	1.80	3.79
Stag	94	3.36	2.33	4.82
Stag	95	2.67	1.69	4.14
Stag	96	2.28	1.56	3.30
Sutil	94	1.57	1.09	2.22
Sutil	95	1.24	0.81	1.84
Sutil	96	2.67	1.82	3.88
Von	94	4.30	2.99	6.14
Von	95	2.26	1.55	3.26
Von	96	2.69	1.77	4.04

A.3.2 Weight density differences between years

Table A.3.2 below lists p-values for the null hypothesis that there is no difference between years in weight density in the same location. No adjustment has been made for multiple comparisions.

Table A.3.2: P-values for differences in weight density between years.

Location	Year	Vs Year	P-value
Harwood	94	95	0.0781
Harwood	95	96	0.9932
Hernando	94	95	0.1783
Hernando	95	96	0.0389
Lloyd	94	95	0.3268
Lloyd	95	96	0.6610
Pendrell	94	95	0.8865
Pendrell	95	96	0.2912
Savary	94	95	0.5393
Savary	95	96	0.2943
Sliammon	94	95	0.4930
Sliammon	95	96	0.3325
Squirrel	94	95	0.1447
Squirrel	95	96	0.0925
Stag	94	95	0.4268
Stag	95	96	0.6013
Sutil	94	95	0.3886
Sutil	95	96	0.0067
Von	94	95	0.0148
Von	95	96	0.5357

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