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Optimum design for shed sampling of eels

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1 Executive Summary

This document is a final report on work carried out under Objective 1 of Ministry of Fisheries project EEL9701, which is titled *Assessment and monitoring of commercial eel fisheries*. The objective is *To develop an optimal sampling design for the determination of size frequency of eels caught in commercial eel fisheries and the age of eels at the minimum legal size*.

It is not possible to provide a single optimal design for eel sampling because no optimisation criteria (e.g., target *c.v.*s) have been specified. However, the material presented here describes some design lessons that can be learnt from the existing data and will allow an optimum design to be developed (within the constraints of these data) once the optimisation criteria have been specified.

The aim of the sampling programme is taken to be to estimate, for the catch from each fishery, the following quantities: the species composition (percentage, by weight, of the catch that is longfin); the mean length and weight of each species; and the mean age at weights 220 g (the minimum legal size) and 500 g for each species. Further, it is assumed that the effectiveness of the programme is measured by the standard errors (*s.e.*s) of these estimates.

Data from the 1995–96 and 1996–97 sampling seasons are described and analysed. Results from these analyses were used to design and execute two experiments that simulate the sampling procedure for a range of sample designs.

The most striking aspect of the data is their degree of heterogeneity. This is evident amongst catchments, between strata (sub-catchments) within a catchment, and between landings within a stratum. Because of this it is concluded that the current practice of subdividing catchments into strata for the purpose of describing catch location is justified, at least for some catchments.

A second conclusion is that it is best to spread the sampling effort for each stratum over as many landings as possible. For a given total sample size substantially greater precision can be achieved by sampling a few eels from many landings rather than many eels from a few landings.

A third effect of this great heterogeneity is that the precision achieved by a given level of sampling effort will vary widely from place to place. For example, with a sampling regime in which 50 eels were measured and 10 otoliths collected from each of five landings (catches), the estimated *s.e.*s varied by a factor of 9 for species composition, 19 for mean weight, and 5 for mean age at the minimum legal size, depending on which area was to be sampled.

There is a clear advantage to be gained by tailoring the otolith sample according to the target weights of 220 g and 500 g. The main consideration is that the distribution of weights of sampled eels should be spread approximately equally about the target, rather than being skewed or off centre.

For areas (strata) where there were sufficient data, formulae are provided to allow the optimisation of the design of future sampling programmes. For size and species composition these are available for 14 areas; for age, only five "stocks" (combinations of area and species) are covered. This restricted coverage is a consequence of the limited extent of existing data: there are few areas with sufficient samples of an adequate size. Even for these areas, the data are relatively few, so predictions derived from the formulae should be considered as approximate only (particularly for mean age). Nevertheless, they should provide a useful first step in optimising the design of future eel shed-sampling programmes. It is likely that this will involve some degree of compromise because the sampling intensity required to achieve target *c.v.*s for some quantities may be much greater than that for others.

Three issues not covered in the above analyses, but relevant to the question of design optimisation, are discussed: sampling costs; the importance of "minor" species; and the pool of fishers from which samples are collected.

2 Introduction

In 1995–96 a shed-sampling scheme was initiated to obtain information about the catch from the commercial fishery for freshwater eels in New Zealand. Two species of eel are caught: shortfin (*Anguilla australis*) and longfin (*A. diefenbachii*). The aim of the work described below is to refine the sampling design using data from the first two years of the scheme.

This document is a final report on work carried out under Objective 1 of Ministry of Fisheries project EEL9701. The objective for that project is "To assess and monitor commercial eel fisheries", and the objectives for 1997–98 include the following.

1. To develop an optimal sampling design for the determination of size frequency of eels caught in commercial eel fisheries and the age of eels at the minimum legal size

2. To monitor the *species composition*, size structure, and age at the minimum legal size *and well above minimum legal size* of priority commercial eel fisheries by sampling 100 landings from the Waikato catchment in the fish processing sheds.

3. To monitor the *species composition*, size structure, and age at the minimum legal size *and well above minimum legal size* of priority commercial eel fisheries by sampling from 100 landings at the major eel processing shed in the South Island.

The reason for presenting Objectives 2 and 3 (and for italicising portions of them) is to highlight a discrepancy between them and Objective 1: the former refer to species composition and age well above minimum legal size, and the latter does not. On the assumption that these quantities are of importance (and thus relevant in the sampling design) this document addresses the following extended version of Objective 1:

> To develop an optimal sampling design for the determination of species composition, size frequency, and the age of eels at, and well above, the minimum legal size, for eels caught in commercial eel fisheries.

This is done using data from the first two years of the shed sampling programme: 1995–96 and 1996–97. The data are described, and simulation experiments based on them are used to investigate the relationship between sample design and the precision of estimates of quantities such as mean size and species composition. It was often necessary to combine data from the two years so as to obtain a sufficiently large sample.

3 Making the objective more specific

Before addressing the above objective it is necessary to make it more specific. To do this we seek answers to three questions.

The first question is "what is meant by an optimal design?". There are two main ways in which a sample survey may be optimised: (a) by finding the most efficient (i.e., lowest cost) design to achieve specified levels of precision, or (b) by finding the design that, for a given cost (or sample size), achieves the greatest precision. The specifications for this project do not state which of these is required, and do not provide the required target levels (of either precision or cost) for either. Consequently, the approach taken here is to provide estimates of the level of precision that is achievable for each of a range of sampling designs. This will allow either type of optimisation to be carried out once target levels have been specified. A particular design issue which is addressed below is whether there is justification for the current practice of dividing catchments into strata.

The second question is "what, precisely, is to be estimated?". The objective mentions species composition, size frequency, and the age of eels at, and well above, the minimum legal size. We will assume that these are represented by the following nine quantities:

> %LFE, the percentage (by weight) of the catch that is longfin eels,
> L_{LFE}, L_{SFE}, the mean lengths of longfins and shortfins in the catch,
> W_{LFE}, W_{SFE}, the mean weights of longfins and shortfins in the catch,
> A_{220}, A_{500}, the mean age at weights 220 g and 500 g, by species, in the catch.

The first measures species composition (and we follow Beentjes & Chisnall (1997, 1998) in calculating this by weight, rather than number). The next four quantities are intended to measure size distribution. There are many other quantities that could be chosen to measure some aspect of size distribution (e.g., median size, the proportion of eels above or below some given size, the range or variance of size), but the mean is the simplest and most obvious. A_{220} clearly measures age at the minimum legal size. No guidance is given in the project specifications about what is meant by a size "well above the minimum legal size". The value of 500 g is used here because it has been chosen (for Objectives 2 and 3 of this project) as being a round number that is as high as possible without making it unduly difficult to find eels of near that size in all fisheries. It is assumed that the effectiveness of the sampling programme is well measured by the standard errors (*s.e.*s) of these nine quantities.

The final question is "what is meant by a fishery". It is assumed that it is intended to estimate each of the above nine quantities for every priority commercial eel fishery (*see* Objectives 2 and 3 above), but there is no guidance in the project specifications as to what is meant by either "priority" or "fishery". We will assume that "fishery" corresponds to what is called a stratum in the next section, and that estimates are to be made for all strata where there are sufficient data.

4 Structure and extent of data

In this section key elements of the structure and extent of the shed-sampling data are described. More detailed information was given by Beentjes & Chisnall (1997, 1998).

Data from two sampling seasons (1995–96 and 1996–97) were available. These data contain information about the catches of certain eel fishers who agreed to participate in the shed-sampling programme. One of the requirements for these participating fishers is that they record where they fished, and keep separate, eels that were caught in different areas. For the purposes of area recording, New Zealand was divided into 28 *catchments*, and each catchment was subdivided into sub-catchments, here called *strata* (e.g., the lower and upper reaches of a river might constitute separate strata). The data were collected at eel processing factories and are organised by *landing*, where a landing is defined as all the eels delivered to a factory on a specific day by a specific fisher and coming from a specific stratum. [What are here called catchments are recorded in the "area" field in the computer database; the strata are as in the "stratum" field, for South Island landings, or the "stratum code" field, for North Island landings].

A total of 280 landings were recorded over the two years, with more landings, and a higher percentage of the total catch, in the South Island (Table 1). Amongst the 280 landings, there were only 26 (20 in 1995–96 and 6 in 1996–97) where the same fisher delivered eels from more than one stratum on the same day. Thus it appears that fishers fish in only one stratum on more than 90% of fishing trips.

Table 1: Summary of landings sampled (number, total weight, and percentage of total catch) by year and island

	North Island			South Island		
	Landings sampled		Percentage of	Landings sampled		Percentage of
Year	Number	Total weight (t)	total catch	Number	Total weight (t)	total catch
1995–96	14	3.0	0.3	126	52.4	11.4
1996–97	38	17.7	2.1	102	37.0	8.8
All	52	20.7	1.2	228	89.4	10.2

For the current analyses it was important to have data for many landings from the same catchment. Of the 28 catchments sampled, there were only 8 for which at least 10 landings were recorded (Table 2). These catchments accounted for more than 80% of all the sampled landings.

Table 2: **Number of landings sampled, by catchment, stratum, and year, for all catchments in which 10 or more landings were sampled.** '–' = no such stratum in this area

A. South Island

	Mataura		Te Waihora*		Oreti		Clutha		Waitaki		Aparima	
Stratum	95–96	96–97	95–96	96–97	95–96	96–97	95–96	96–97	95–96	96–97	95–96	96–97
1	23	20	10	6	4	6	5	4	1	3	8	2
2	7	1	4	0	4	3	8	4	6	3	2	3
3	6	0	0	5	6	4	3	0	7	2	–	–
4	3	0	6	5	–	–	0	1	–	–	–	–

* Lake Ellesmere

B. North Island

	Waikato		Hauraki	
Stratum	95–96	96–97	95–96	96–97
1	0	7	–	–
2	0	3	–	–
3	1	0	–	–
4	1	1	1	0
5	1	4	0	1
6	0	3	0	3
7	–	–	2	3
9	4	4	–	–
10	1	1	–	–
51	1	0	–	–

For each landing the total weight of eels and the stratum in which they were caught was recorded. Then a random sample of eels was taken from the landing, and species, length, and weight was recorded for each eel in this sample. The sample size varied from landing to landing but was typically about 40 kg, consisted of 100 eels, and was about 20% of the landing by weight (Figure 1).

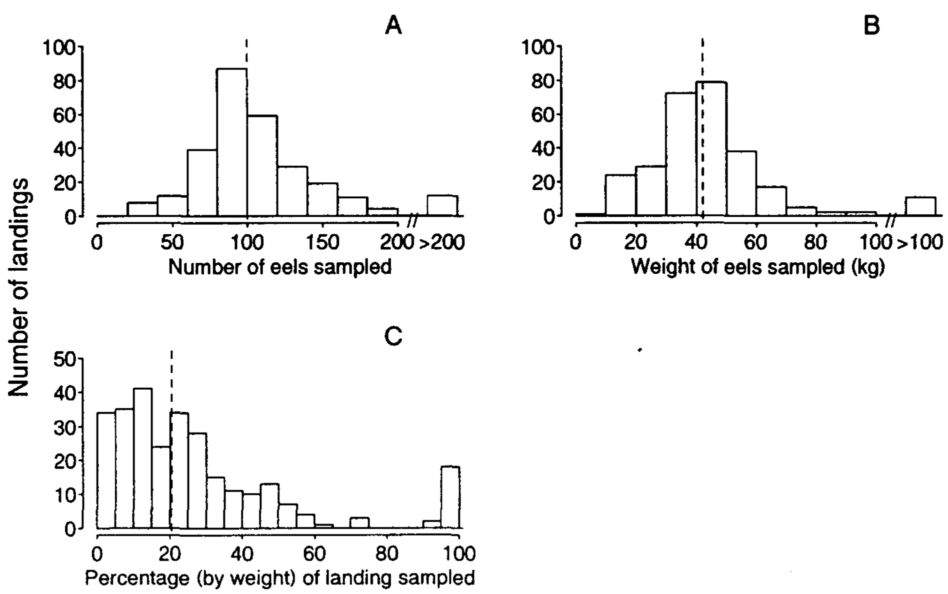

Figure 1: Histograms of sample size per landing (both sampling seasons combined): A, number of eels; B, weight of eels; C, percentage of total landing weight. Vertical broken lines are median values.

5 Size (length and weight) and species composition

5.1 Description of data

The mean size of eels varied widely from landing to landing and tended to be more variable for shortfins than for longfins (Figure 2). Landings in which the mean size was high tended to have more variation in size (i.e., the standard deviation of size was high).

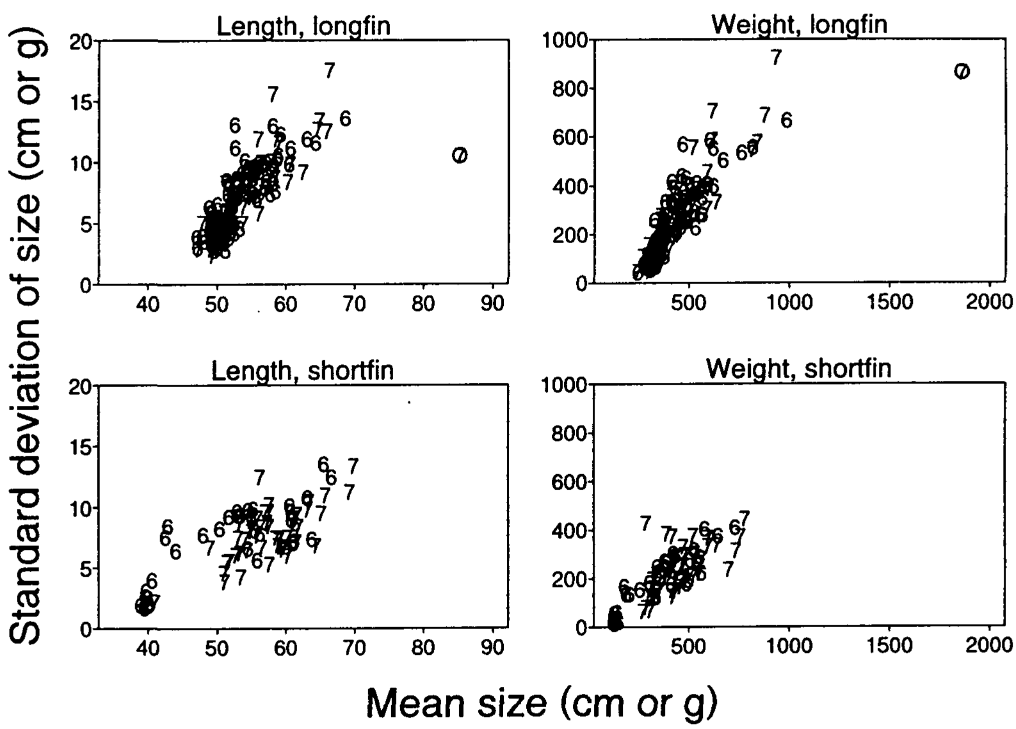

Figure 2: Mean size (length or weight) of eels in a landing plotted against the standard deviation of size. Each plotted point corresponds to a landing ('6' = 1995–96, '7' = 1996–97; landings where fewer than 50 eels of a species were measured were excluded). The circled point in the upper panels is from landing 972506, which was from stratum 1 in the Waikato catchment.

The variability in species composition amongst landings is shown in Figure 3. In the South Island, longfins were dominant, except in Te Waihora and the lower reaches (stratum 1) of some catchments (e.g., Mataura and Waitaki).

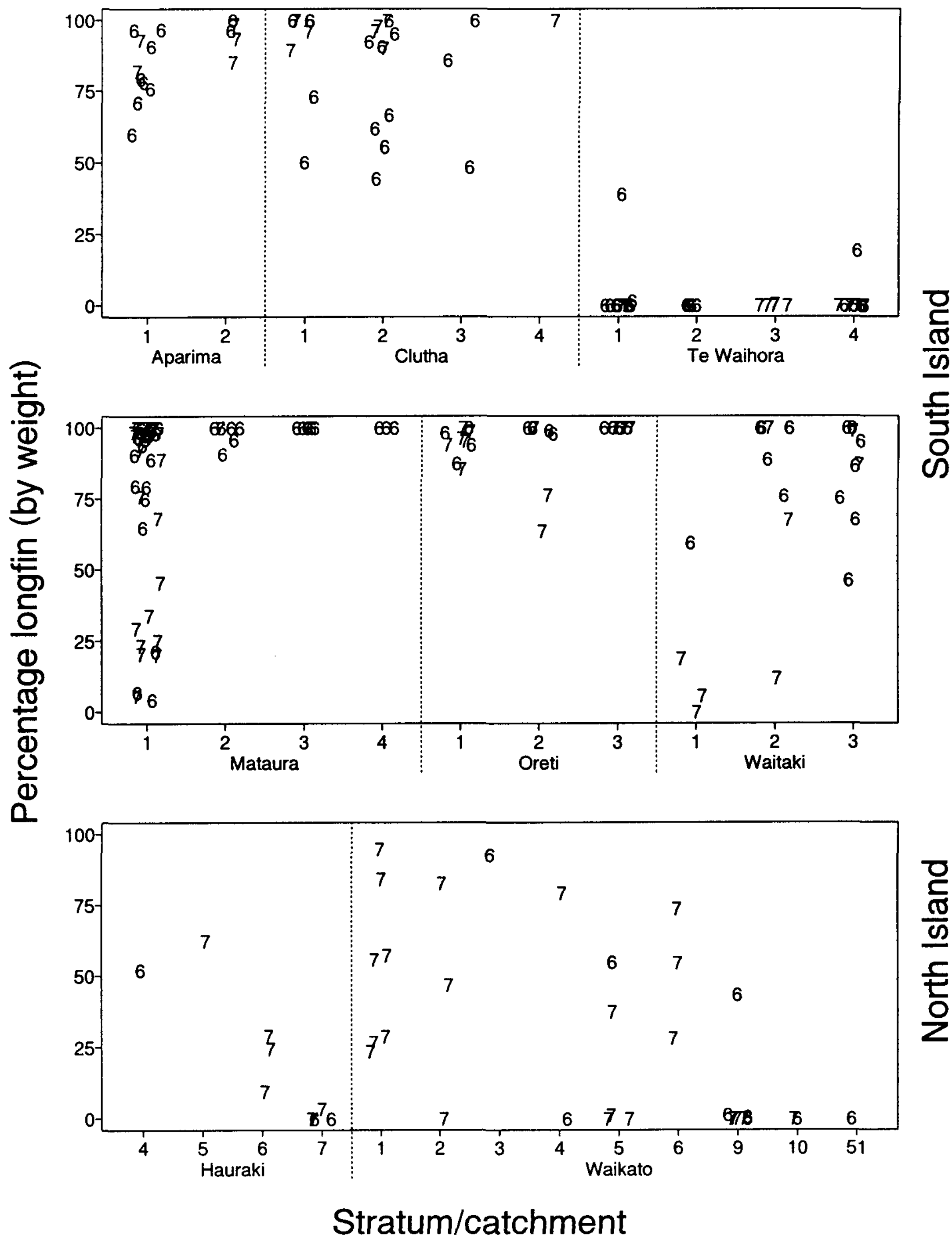

Figure 3: Percentage (by weight) of longfins in each landing, plotted by catchment and stratum for all catchments with at least 10 landings. Each plotted point corresponds to a landing ('6' = 1995–96, '7' = 1996–97). South Island catchments are shown in the upper two panels; those for the North Island are in the bottom panel.

Variability in mean length, within and between strata, is shown in Figure 4. In some catchments there appear to be consistent between-stratum differences in eel size (e.g., longfins in Mataura and shortfins in Te Waihora), but there are often too few samples to be sure whether such differences exist. In South Island strata where both longfin and shortfin occur, mean length is typically greater for shortfin.

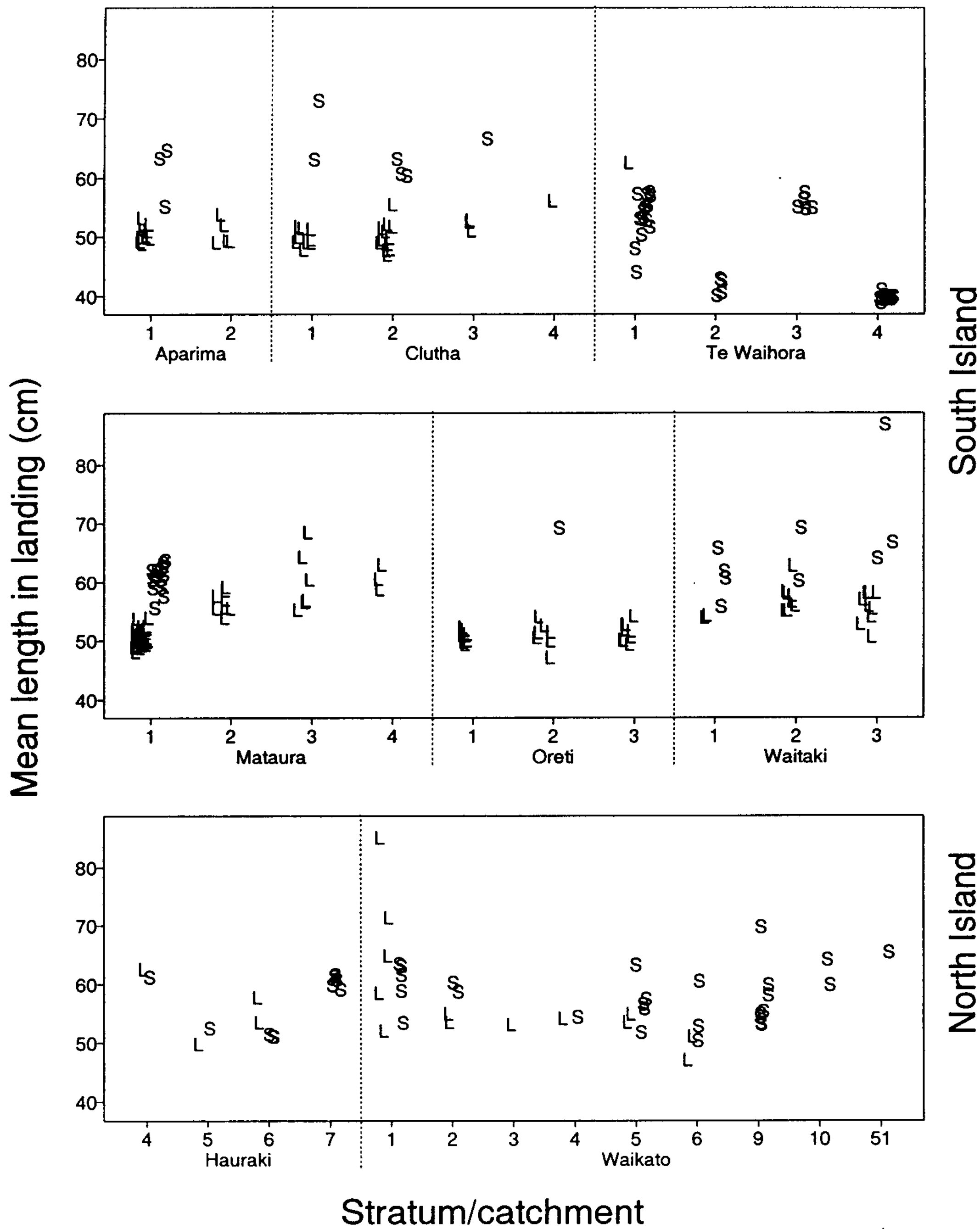

Figure 4: Mean length of eels in each landing, plotted by species, catchment, and stratum for all catchments with at least 10 landings. Each plotted point corresponds to a species ('L' = longfin, 'S' = shortfin) in a landing (mean lengths associated with fewer than 20 eels are not plotted). South Island catchments are shown in the upper two panels; those for the North Island are in the bottom panel. The two sampling seasons are combined in these plots.

5.2 Differences Between Strata

A series of randomisation tests (*see* Appendix 1 for details) was used to test for differences in mean size and/or species composition (percentage, by weight, of longfin) between strata in the same catchment (combining data from the two sampling seasons). These tests were carried out for pairs of strata within the same catchment where there were sufficient data. For the South Island river catchments only adjacent strata were compared. Of 26 pairs of strata that were tested, 15 showed a significant difference in at least one variable (Table 3).

Table 3: Results of randomisation tests for differences in species composition and mean size between selected pairs of strata. The first three columns give the catchment, the two strata that are being compared, and the number of landings in each stratum. In the remaining columns '✓' means there is a significant difference between the strata ($P < 0.05$) and '-' means that there was insufficient data to carry out a test

		Number		Species	Longfin		Shortfin	
Catchment	Strata	of landings		composition	Length	Weight	Length	Weight
Mataura	1 2	43	8		✓	✓	✓	✓
	2 3	8	6		✓	✓	-	-
	3 4	6	3				-	-
	2 4	8	3		✓	✓	-	-
Te Waihora	1 2	16	4		-	-	✓	✓
	1 3	16	5		-	-		
	1 4	16	11				✓	✓
	2 3	4	5		-	-	✓	✓
	2 4	4	11		-	-	✓	✓
	3 4	5	11		-	-	✓	✓
Oreti	1 2	10	7					
	2 3	7	10	✓			-	-
Clutha	1 2	9	12				✓	
	2 3	12	3					
Waitaki	1 2	4	9	✓	✓	✓		
	2 3	9	9					
Aparima	1 2	10	5					
Waikato	9 1	8	7	✓				
	9 5	8	5	✓				
	9 6	8	3	✓				
	9 2	8	3	✓				✓
	1 5	7	5					
	1 6	7	3					
	1 2	7	3					
	5 6	5	3					
	5 2	5	3					

5.3 Precision of Estimation (Size and Species Composition)

The precision of estimates of mean size and species composition was investigated using a purpose-written computer program that uses a bootstrap approach to simulate shed sampling (*see* Appendix 2 for details). Simulations were carried out for 14 data sets (Table 4). Most of these correspond to a single stratum, and the criterion for inclusion was that there should be at least eight landings in each (in the two sampling seasons combined). To boost the number of data sets the Mataura stratum 1 data was split by year, and adjacent strata were combined when the tests in Table 3 indicated no significant difference. For convenience, all 14 data sets will be referred to as strata in what follows. Also, results are presented for a stratum/species combination only when that species was present in at least half the landings for that stratum.

Table 4: Data sets ("strata") used in shed-sampling simulations, with number of landings, species composition (%LFE), and species included in results. Where a sampling season is not specified, data from the two seasons were combined. ***The letter codes are used in the table header of Appendix 3***

Code	Description	Number of landings	%LFE	Species included Longfin	Species included Shortfin
A	Mataura stratum 1 1995–96	23	84	✓	✓
B	Mataura stratum 1 1996–97	20	68	✓	✓
C	Mataura stratum 2	8	98	✓	
D	Mataura strata 3&4	9	100	✓	
E	Clutha stratum 1	9	89	✓	
F	Clutha stratum 2	12	71	✓	✓
G	Waitaki stratum 2	9	89	✓	
H	Waitaki stratum 3	9	86	✓	✓
I	Oreti strata 1&2	17	94	✓	✓
J	Oreti stratum 3	10	100	✓	
K	Aparima stratum 1	10	85	✓	✓
L	Te Waihora stratum 1	16	3		✓
M	Te Waihora stratum 4	11	2		✓
N	Waikato stratum 9	8	5		✓

The two variables which controlled the sample design were m_{land}, the number of landings to be sampled, and n_{eel}, the number of eels to be measured in each landing. For each stratum, 1000 catch samples were generated for every combination of m_{land} = 3, 5, 10, and 20 and n_{eel} = 10, 20, 50, and 100. For each catch sample, five quantities were calculated: the percentage longfin (by weight), *%LFE*, and the mean lengths and weights by species, L_{LFE}, L_{SFE}, W_{LFE}, and W_{SFE}. The standard deviations of these quantities over the 1000 catch samples were calculated as estimates of their *s.e.*s for the given stratum and values of m_{land} and n_{eel}. Full results from this experiment are given in Appendix 3.

The results for the two years of data for Mataura stratum 1 illustrate two patterns that occur across the various strata (Figure 5). First, the *s.e.*s for mean size (length or weight) are much greater for one species than for the other. The rarer species for the stratum always had the higher *s.e.* (19% of eels measured in Mataura stratum 1 were shortfins). Second, the *s.e.* for each of the five quantities is mostly determined by the number of landings sampled, m_{land}. In general, the number of eels measured per landing, n_{eel}, has only a slight effect. An exception to this is when m_{land} is small and the species is relatively rare in the stratum (e.g., m_{land} = 3 for shortfin eels in Figure 5). This is understandable because, with a small number of landings, the total number of shortfins measured in Mataura stratum 1 will be very small unless n_{eel} is large.

Another feature of the results in Figure 5 is that the between-year difference in *s.e.*s is relatively small compared to the variation with different values of m_{land}. It is not possible to say whether this result is general because there is only one stratum with sufficient data to make between-year comparisons.

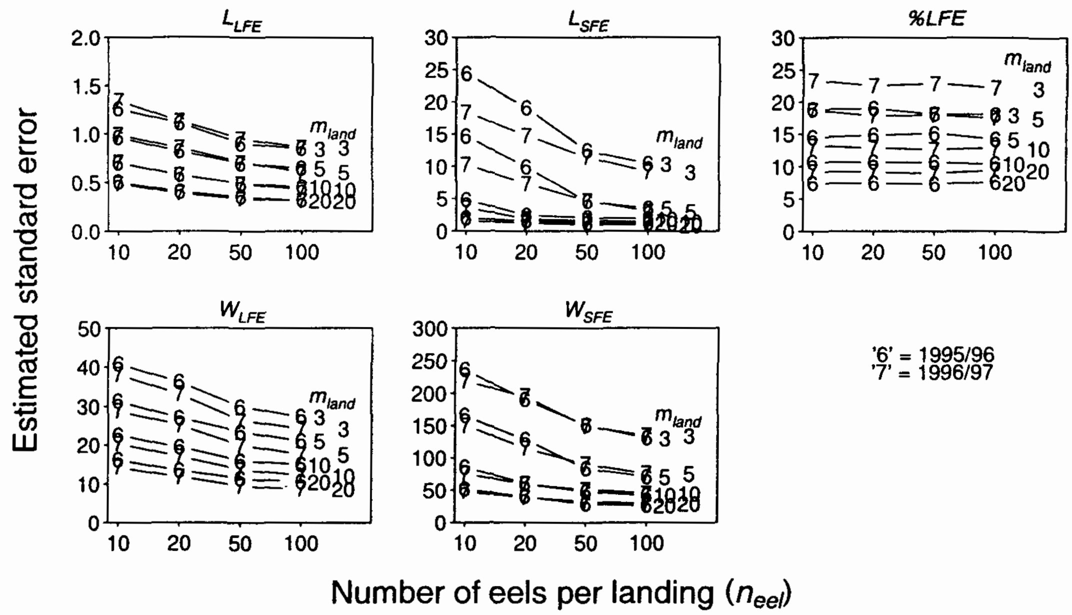

Figure 5: Results of shed-sampling simulations for Mataura stratum 1. Estimated *s.e.*s for five quantities (L_{LFE}, L_{SFE}, W_{LFE}, W_{SFE}, and *%LFE*) are plotted against the number of eels sampled per landing, n_{eel}, for each of four values of m_{land}, the number of landings sampled. Results with the same value of m_{land} are joined by lines, and the two sampling years are distinguished by different plotting symbols.

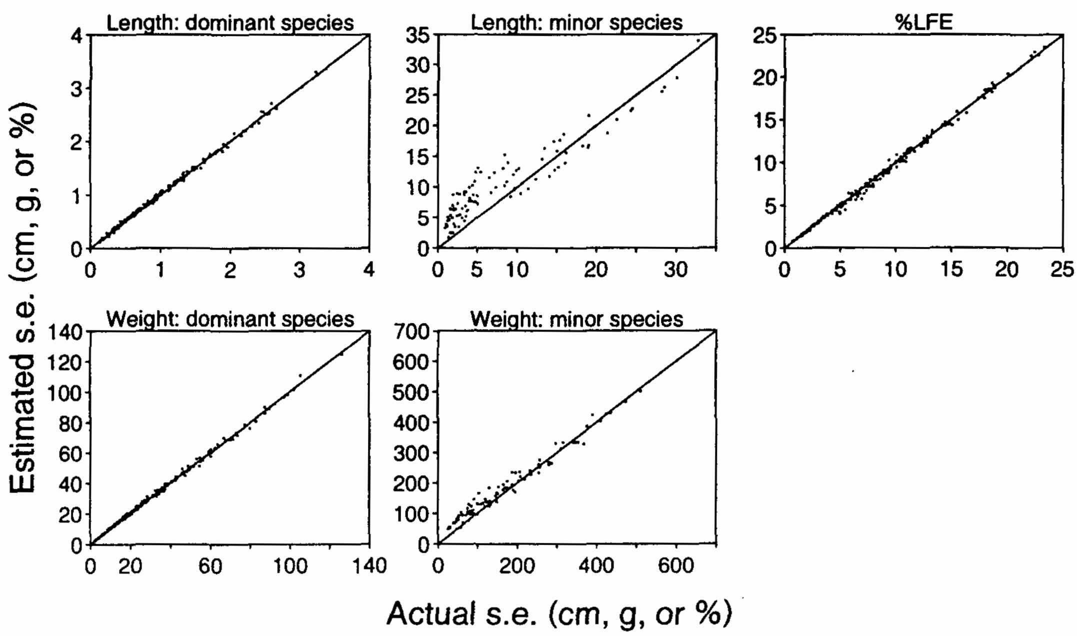

Figure 6: Actual *s.e.*s (from simulation experiment) plotted against those estimated using equation (1) and the coefficients in Table 5. For mean sizes (L_{LFE}, L_{SFE}, W_{LFE} and W_{SFE}) results for the two species are combined but are plotted separately for dominant species (more than 66% of the catch for the stratum) and minor species (less that 33% of the catch). (There were no strata where a species was between 33% and 66% of the catch).

A striking aspect of the results from this experiment is that that the precision achieved from a given sampling design varies very much from stratum to stratum. For example, with m_{land} =10 and n_{eel} = 100 the expected *s.e.* varies from 1.1% to 12.9% for %LFE, from 0.2 cm to 1.8 cm for length, and from 3 g to 55 g for weight (Appendix 3). The ranges for length and weight are only for the dominant species in each stratum; they would be much wider if both species were included.

It would be useful to be able to predict the *s.e.*s for sample designs (i.e., values of m_{land} and n_{eel}) that were not covered in this experiment. An obvious candidate prediction equation is

$$\text{standard error} = \left(\frac{\sigma^2_{bet}}{m_{land}} + \frac{\sigma^2_{with}}{m_{land} n_{eel}} \right)^{0.5} \tag{1}$$

where σ^2_{bet} and σ^2_{with} are the between- and within-landing variances (different for each stratum). This equation would be exactly correct if the within-landing variance in size was the same for all landings from the same stratum and if all landings were of the same weight. These conditions do not hold true, but to see whether, nevertheless, this equation might be a reasonable approximation it was fitted to the results in Appendix 3 (a least-squares regression was used and regression coefficients were constrained to be non-negative). The fit was found to be good except for *s.e.*s of size (length or weight) where the species considered was minor for that stratum (less than 33% by weight) (Figure 6).

Table 5: Estimated coefficients, σ_{bet}, σ_{with} from fits of the predictive equation (1) to the *s.e.*s in Appendix 3. '*' = no shortfins in samples from this stratum; '-' = results not presented because species occurs in less than half the landings

	%LFE		L_{LFE}		L_{SFE}		W_{LFE}		W_{SFE}	
Stratum	σ_{bet}	σ_{with}	σ_{bet}	σ_{with}	σ_{bet}	σ_{with}	σ_{bet}	σ_{with}	σ_{bet}	σ_{with}
Mataura stratum 1 1995–96	31.8	26.1	1.39	5.39	9.88	119	45.5	174	180	1100
Mataura stratum 1 1996–97	38.8	38.2	1.38	5.87	11.9	83.6	38.9	170	200	967
Mataura stratum 2	3.18	15.6	1.63	9.11	-	-	65.4	328	-	-
Mataura strata 3&4	*	*	4.1	10.2	-	-	164	445	-	-
Clutha stratum 1	19.5	36	1.29	5.14	-	-	27	133	-	-
Clutha stratum 2	22.6	49.5	2.1	6.15	11.3	119	58.7	183	351	2060
Waitaki stratum 2	31.4	50.3	2.11	10.5	-	-	69.5	383	-	-
Waitaki stratum 3	18.7	37.6	2.44	9.24	18	141	74.7	325	650	2570
Oreti strata 1&2	11.2	25.7	1.44	5.21	21.3	173	34	155	363	2020
Oreti stratum 3	*	*	1.5	5.65	-	-	40.1	204	-	-
Aparima stratum 1	12.7	48	1.33	5.32	0	76.4	23.7	168	96.3	1340
Te Waihora stratum 1	11	0	-	-	3.64	7.79	-	-	84.8	239
Te Waihora stratum 4	5.96	15.4	-	-	0.329	3.61	-	-	8.52	30.5
Waikato stratum 9	17.4	31.4	-	-	5.58	5.17	-	-	153	149

With equation (1), and the constants in Table 5, we may now ask what level of sampling would be required to achieve specified target *s.e.*s. For example, with a target *s.e.* e, the number of landings, m_{land}, that should be sampled for a given value of n_{eel} is given by

$$m_{land} = \frac{\sigma^2_{bet} + \sigma^2_{with} / n_{eel}}{e^2}$$

and the number of eels, n_{eel}, that should be sampled for a given value of m_{land} is given by

$$n_{eel} = \frac{\sigma^2_{with}}{m_{land}e^2 - \sigma^2_{bet}}$$

The example given in Table 6 (using the first of these equations) shows that the required sampling effort varies strongly from stratum to stratum.

Table 6: The estimated number of landings that would need to be sampled, by stratum, to achieve *s.e.*s of: 10% in %LFE, 1 cm in the mean length of the dominant species, or 30 g in the mean weight of the dominant species. A sample size of 100 for each landing is assumed (i.e., n_{eel} = 100). '–' = only longfins found in this stratum

Stratum	%LFE	Length	Weight
Mataura stratum 1 1995–96	11	3	3
Mataura stratum 1 1996–97	16	3	3
Mataura stratum 2	1	4	6
Mataura strata 3&4	–	18	33
Clutha stratum 1	4	2	2
Clutha stratum 2	6	5	5
Waitaki stratum 2	11	6	8
Waitaki stratum 3	4	7	8
Oreti strata 1&2	2	3	2
Oreti stratum 3	–	3	3
Aparima stratum 1	2	3	1
Te Waihora stratum 1	2	14	9
Te Waihora stratum 4	1	1	1
Waikato stratum 9	4	32	27

6 Age data

In some landings, otoliths were collected from a subsample of the eels that were measured. The otoliths were broken and burned and age (years in freshwater) was estimated.

6.1 Description of data

Just over 2000 otoliths were collected from each island, but more landings were sampled in the South Island (Table 7) and so the median sample size was higher in the North Island (Figure 7). Otoliths were collected from almost all North Island landings, and just over 50% of those in the South Island (Table 7).

Table 7: Summary of otolith samples (landings sampled for otoliths, by number and percentage, and number of otoliths collected) by year and island

	North Island			South Island		
	Landings sampled		Otoliths	Landings sampled		Otoliths
Year	number	percentage	collected	number	percentage	collected
1995–96	14	100	281	63	50	1408
1996–97	35	92	1845	69	68	959
All	49	94	2126	132	58	2367

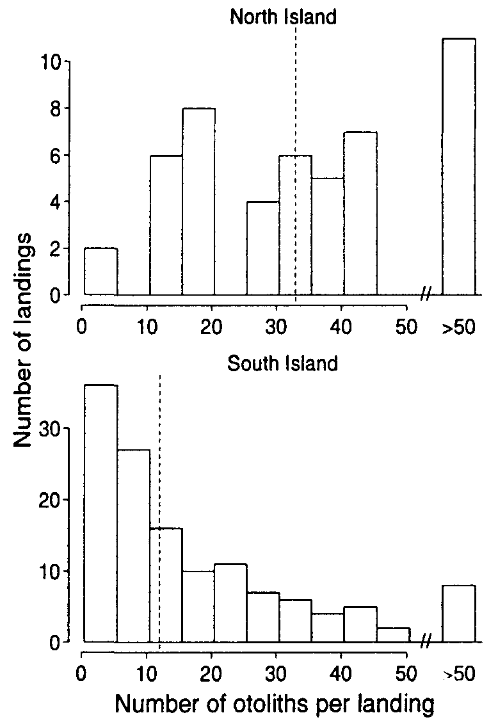

Figure 7: Histograms of number of otoliths collected per landing for each island. Vertical dotted lines indicate median values.

For eels of the same species in the same stratum, the relationship between age and the logarithm of weight seems to be reasonably linear (Figure 8).

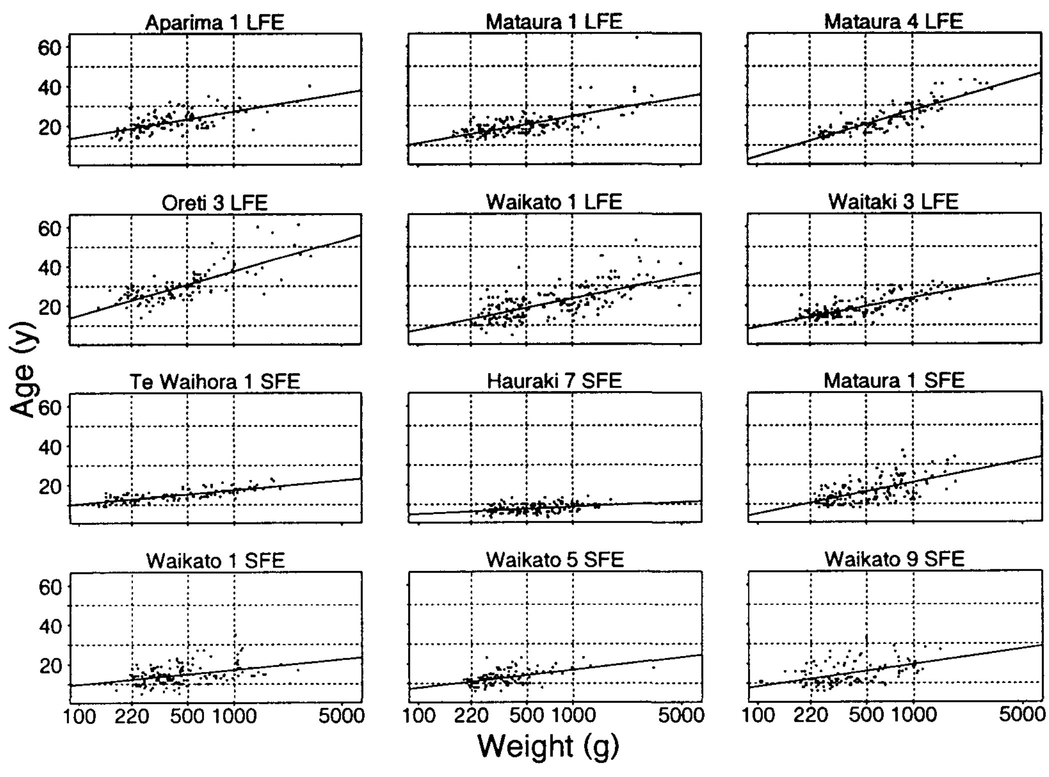

Figure 8: Plots of age against weight (log scale), with fitted regression line, for all "stocks" (combinations of stratum and species) with more than 100 otoliths. Each point is a single eel.

6.2 Variability amongst landings

An important issue with regard to sample design aimed at estimating A_{220} and A_{500} is whether the age-weight relationship varies significantly between landings from the same stratum. A randomisation test was used to investigate this. The quantities A_{220} and A_{500} were calculated for each landing in a stratum by regressing age against log(weight) and using the regression equation to calculate the mean ages at weights 220 g and 500 g, respectively. Then the variance of all the A_{220} estimates for a stratum was calculated (and similarly for A_{500}). These variances were taken as the statistics for the randomisation tests (i.e., they were compared with 999 other estimates of the same quantities calculated after randomly reassigning the age-weight data from each eel amongst the landings). For each species, the test was restricted to landings with at least 20 otoliths, and to strata with at least three such landings. There were only five "stocks" (combinations of stratum and species) satisfying this criterion. Results were significant for both A_{220} and A_{500} on shortfin in Waikato stratum 1, and marginally significant for A_{500} on longfin in Waikato stratum 1 and shortfin in Hauraki stratum 7 (all in the North Island) (Table 8).

Table 8: Significance levels for randomisation tests designed to detect between-landing heterogeneity in A_{220} and A_{500} (mean ages at 220 g and 500 g)

	Significance level	
Stock	A_{220}	A_{500}
Hauraki stratum 7 shortfin	0.70	0.10
Waikato stratum 1 longfin	0.29	0.07
Waitaki stratum 3 longfin	0.38	0.15
Te Waihora stratum 1 shortfin	0.50	0.39
Waikato stratum 1shortfin	0.00	0.00

Another way to illustrate the variability amongst landings is by comparing the results of regressions of age on log(weight) (Table 9; Figure 9). The mean ages in Waikato stratum 1 (for both species) are much more variable than they are for the other stocks (Figure 9A). The variability in weight, for eels of a given age, is greatest for longfins in Waikato stratum 1 and least for shortfins in Te Waihora stratum 1 and Hauraki stratum 7 (Figure 9B).

Table 9: Results of fitting linear regressions of age on log(weight) to the data from all landings covered by the randomisation test: intercept and slope of the regression line, standard deviation of the residuals, σ, and estimated mean ages at weights 220 g and 500 g

Stock	Landing	Otoliths	Intercept	Slope	σ	A_{220}	A_{500}
Waikato stratum 1 longfin	972502	71	-9.1	5	7.5	18.1	22.2
	972518	30	-24	6.8	4.1	12.8	18.4
	972510	21	-10.5	4.5	3.4	13.8	17.4
	972506	25	-29.3	7.7	5.8	12	18.3
Waitaki stratum 3 longfin	972012	24	-16.3	5.7	2.9	14.3	18.9
	972038	24	-20.2	6.4	2.5	14.4	19.7
	952020	49	-19.8	6.1	3.4	13.2	18.2
	962026	38	-21.1	6.7	3.7	14.9	20.4
Te Waihora stratum 1 shortfin	952010	39	-6.1	3.5	1.9	12.6	15.5
	962074	28	-1.6	2.7	1.9	12.7	14.9
	952011	25	3.5	1.8	1.6	13.3	14.9
Hauraki stratum 7 shortfin	972507	39	-4.6	1.9	2.6	5.5	7
	972505	36	5.2	0.3	1.8	6.7	7
	962503	28	-1	1.4	1.5	6.6	7.8
	962506	40	-6.4	2.3	2	6.1	8
Waikato stratum 1 shortfin	972502	57	1.1	2.1	4.1	12.3	14
	972527	25	-13.2	5.1	2.2	14.5	18.7
	972522	26	-59.4	12.1	4.1	6	16
	972510	24	-8.3	3.6	3.5	11.3	14.3

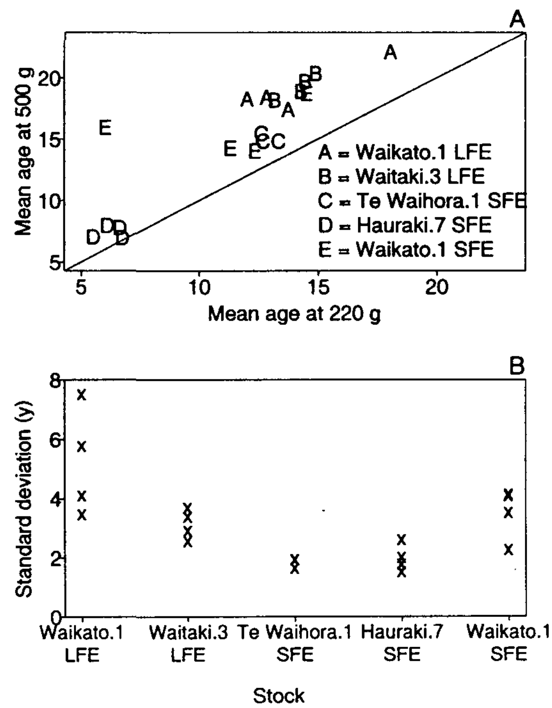

Figure 9: Plots of results in Table 9: A, estimates of A_{220}, mean age at 220 g, plotted against A_{500}, the mean age at 500 g; B, the standard deviation, σ, of the residuals of the regressions of age on log(weight). Each point in either plot represents a landing.

6.3 Precision of estimation of mean age

This section describes a simulation experiment aimed at determining how the precision of estimates of A_{220} and A_{500} is likely to vary from stratum to stratum and with changes in sampling design. The simulation procedures are described in Appendix 4. There were three design variables: m_{land}, the number of landings from which otoliths were sampled for a given stock; n_{oto}, the total number of otoliths that were sampled for that stock; and W_{dist}, the distribution from which eel weights were sampled. This last variable is included because the current (1997–98) sampling strategy is to restrict otolith samples to eels that are close in weight to either 220 g (say 200–240) or 500 g (say 450–550).

Simulations were carried out for the five stocks in Table 9 and using all combinations of n_{oto} = 10, 20, 50, or 100, and m_{land} = 1, 2, 3, or 5. For each simulated sample, A_{220} (or A_{500}) was estimated by regressing age against log(weight) and evaluating the regression equation at log(220) [or log(500)]. Default values for W_{dist} were U(200,240) or U(450,550), where U(a,b) is the uniform distribution on the interval (a,b). 1000 samples were simulated for each combination of design variable values.

An obvious feature of the results from the simulations with the defaults values of W_{dist} is that *s.e.*s for both species in Waikato stratum 1 were much greater, for the same sampling effort, than those for other stocks (Figure 10). This is to be expected, given their much greater scatter in Figure 9A. For this stratum there was also a greater advantage in spreading the otolith sample over several landings. When samples are spread over five landings rather than just one, *s.e.*s are reduced by an average of 41% for the two stocks in Waikato stratum 1, compared to 26% for all the other stocks (for the range of n_{oto} values considered).

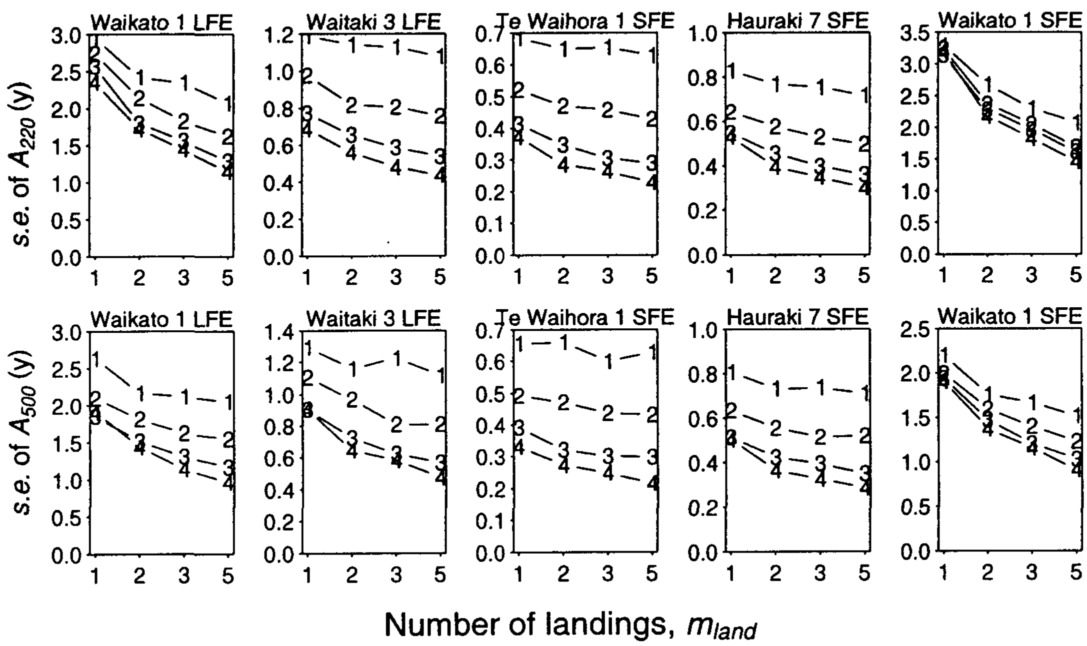

Figure 10: Estimates of the *s.e.*s of A_{220} (upper panels) and A_{500} (lower panels) for five stocks plotted as functions of the number of otoliths collected, n_{oto}, and the number of landings sampled, m_{land}. Plotting symbols: 1 – n_{oto} = 10; 2 – n_{oto} = 20; 3 – n_{oto} = 50; 4 – n_{oto} = 100. In all cases otolith weights were picked at random between 200 g and 240 g or between 450 g and 550 g [i.e., W_{dist} took the default values of U(200,240) or U(450,550)].

Two sets of alternative values for W_{dist} were considered. First, to see what would happen if otoliths were sampled at random (with no constraint on eel size), W_{dist} was set to be the same as the observed weight distribution for each stock. I called these the 'empirical' distributions (Figure 11, left panels). The effect of using these distributions depended strongly on which mean age was being estimated (A_{220} or A_{500}) and, to a lesser extent, on the stock. For A_{220}, *s.e.*s increased substantially for most stocks (more than 30% for all but one stock, and as high as 82%); for A_{500}, increases were only 2% to 14% (Table 10). These results reflect how important it is that the distribution of weights in the sample be centred on the target weight. For all stocks the centre of the empirical distribution is much closer to 500g than to 220 g.

The second set of alternative values for W_{dist} is shown in the right-hand panels of Figure 11. They address a particular sampling problem: the difficulty of obtaining sufficiently many eels of weight near 220 g – particularly those less than this weight. Although the target weight distribution may be U(200,240), the actual distribution may be skewed, like T(200,240). Also, the requirement to obtain a specified number of otoliths may require an off-centre distribution like U(200,300). The effect of the skewed distribution is to increase the *s.e.* of A_{220} by 5–18%; with the off-centre distribution the effect is worse, with increases of 10–32% (*see* Table 10).

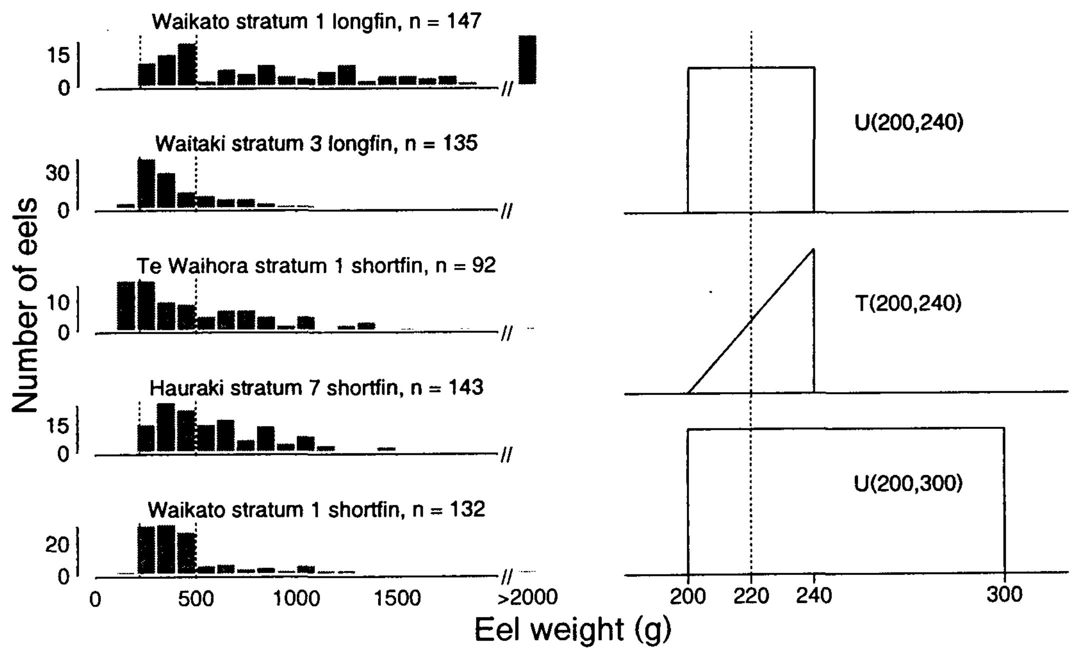

Figure 11: Alternative values, of W_{dist}, the distribution from which eel weights were sampled in estimating A_{220} and A_{500}. The left-hand panels contain the 'empirical' distributions – the actual distributions of eel weight in the combined 1995–96 and 1996–97 samples. The right-hand panels contain three possible distributions in samples for A_{220}: the default distribution, U(200,240); a triangular distribution, T(200,240), centred at 200 g; and an off-centre uniform distribution, U(200,300). The vertical broken lines mark the target weights of 220 g and 500 g.

Table 10: **The average percentage increase in the estimated *s.e.* (of either A_{220} or A_{500}) that would occur from using a weight sampling distribution, W_{dist}, other than the default distributions (U(200,240) or U(450,550)). Percentage increases are averaged over all combinations of n_{oto} and m_{land}. The various alternative weight distributions are shown in Figure 11**

	Estimating A_{220}			Estimating A_{500}
Stock	**Empirical**	**T(200,240)**	**U(200,300)**	**Empirical**
Waikato stratum 1 longfin	48	11	18	14
Waitaki stratum 3 longfin	34	16	29	6
Te Waihora stratum 1 shortfin	30	18	32	5
Hauraki stratum 7 shortfin	82	15	27	2
Waikato stratum 1 shortfin	13	5	10	4

Another obvious set of alternative values of W_{dist} to consider would be distributions that are centred on the target weight but are of different width. For example, it might be expected that choosing U(250,750) would produce estimates of A_{500} markedly less precise than would the default U(450,550), because the weights of sampled eels would not be as close to the target weight of 500 g. However, this turns out not to be true. With the former distribution *s.e.*s were, on average, only about 1% larger than with the default distribution. An examination of the statistics of regression (e.g., Draper & Smith 1981) shows that the *s.e.* of A_{500} is independent of the width of the weight distribution as long as this distribution has mean 500 g (or, more correctly, the mean of log(weight) is log(500)). Nonetheless robustness considerations (see Conclusions) make U(450,550) preferable to U(250,750).

It would be useful to be able to derive a formula to represent the results in Figure 10 (as was done with the results in Section 5.3). The obvious candidate formula in this case is

$$\text{standard error} = \left(\frac{\sigma_{bet}^2}{m_{land}} + \frac{\sigma_{with}^2}{n_{oto}} \right)^{0.5} \tag{2}$$

Note that equation (2) is effectively the same as equation (1) but appears slightly different because n_{eel} is the number of eels per landing and n_{oto} is the total number of otoliths (across all landings). This equation was fitted by least squares to the results in Figure 10. Because it fitted very well, with a root-mean-square error of only 0.03 y, it seemed sufficient to present only the estimated coefficients (Table 11) and not the direct simulation results.

Table 11: Estimated coefficients, σ_{bet}, σ_{with} (y) from fits of the predictive equation (2) to the *s.e.*s in Figure 10

	A_{220}		A_{500}	
Stock	σ_{bet}	σ_{with}	σ_{bet}	σ_{with}
Waikato stratum 1 longfin	2.35	5.72	1.74	5.91
Waitaki stratum 3 longfin	0.61	3.3	0.79	3.34
Te Waihora stratum 1 shortfin	0.30	1.94	0.26	1.91
Hauraki stratum 7 shortfin	0.46	2.18	0.43	2.15
Waikato stratum 1 shortfin	3.08	4.57	1.85	3.92

By inverting equation (2) we can estimate the number of otoliths that would be required to meet a target *s.e.* for a given number of landings. Examples of the results of such calculations are given in Table 12. They show how very much the required sampling effort varies from stock to stock.

Table 12: The estimated number of otoliths required, by stock, to achieve various target *s.e.*s in estimating A_{220} or A_{500}, assuming that the otolith sample will be spread over 5 landings (i.e., m_{land} = 5). '-' = target s.e. not achievable with 5 landings

	s.e. = 2 y		*s.e.* = 1.5 y		*s.e.* = 1 y		*s.e.* = 0.5 y	
Stock	A_{220}	A_{500}	A_{220}	A_{500}	A_{220}	A_{500}	A_{220}	A_{500}
Waikato stratum 1 longfin	12	11	29	22	-	89	-	-
Waitaki stratum 3 longfin	<10	<10	<10	<10	12	13	62	90
Te Waihora stratum 1 shortfin	<10	<10	<10	<10	<10	<10	17	16
Hauraki stratum 7 shortfin	<10	<10	<10	<10	<10	<10	23	22
Waikato stratum 1 shortfin	10	<10	59	10	-	49	-	-

7. Other optimisation issues

There are three further issues that fall outside the scope of the above analyses but which are relevant to the question of design optimisation. The first is sampling costs. These are primarily for samplers' time (but could include purchase of samples) and will be important in determining how many eels should be measured from each landing. Although there is not much gain in precision from measuring 100 eels per landing rather than 50, the marginal cost of the additional 50 is small. There is clear scope for a cost-benefit analysis here. In addressing this question it will be important to consider the second issue – the minor species in each stratum. In all of the 14 strata in Table 5 in which more than one species was caught there was a "dominant" species (always more than 66% of the total catch) and a "minor" species (always less than 33%). The question is, do we care about the minor species? If it is considered important to have good estimates of the mean size of both species then much larger samples will be required from each landing. If only the dominant species is important then smaller samples would be sufficient. (Another consideration is that the measured sample must be large enough to provide sufficiently many eels near the target weights for otolith sampling.)

The third issue concerns the pool of fishers whose catch is sampled. Ideally this should be as wide as possible. The usefulness of the samples is severely restricted if they cannot be taken as representative of the total catch of both participating and non-participating fishers. There could be a problem, for example, if some of the non-participating fishers had a pattern of fishing that was markedly different from that of the sampled fishers. One possible constraint is that, where they fish in more than one stratum in the same trip, participating fishers are required to keep separate the catches from the different strata. This may be seen as too onerous by some fishers. However, the data gathered to date show that the participating fishers stuck to one stratum in more than 90% of fishing trips. It may be desirable not to insist on the separation of catches as long as fishers record where they have fished. This would mean not being able to sample some landings (those where catches from several strata are mixed) but would increase the pool of available landings and thus the likelihood that the samples are representative of the total catch.

There is another possible advantage of widening the pool of participating fishers. Ideally, a sampling programme would set a target number of landings to be sampled for each stratum. The larger the pool of participating fishers, the greater the chance that the target will be met.

8. Conclusions

The most striking aspect of the shed-sampling data is the degree of heterogeneity in them. This is evident amongst catchments, between strata (sub-catchments) within a catchment, and between landings within a stratum. This means that, as a general rule, eels sampled in the same stratum tend to be more similar to each other than to those from other strata in the same catchment. Similarly, eels from the same landing tend to be more like each other than they are like those in other landings from the same stratum. This heterogeneity has three important consequences for sampling design. The first is that the current practice of subdividing catchments into strata for the purpose of describing catch location seems justified, at least for some catchments.

Second, it is best to spread the sampling effort for each stratum over as many landings as possible. This can be illustrated by two examples. If mean age at a given weight is to be estimated from a sample of 50 otoliths then the standard error (*s.e.*) will be 25–50% lower if the otoliths are spread over five landings rather than being taken from a single landing. Or, for a sample of 500 eels to estimate mean length and mean weight, the *s.e.* is likely to be 20–30% smaller if 50 eels are measured from each of 10 landings than if 100 eels are measured from each of 5 landings.

The third consequence of this heterogeneity is that the precision achieved by a given level of sampling effort will vary widely from place to place. For example, suppose we decide to measure 50 eels, and take 10 otoliths, from each of five landings in a stratum. Then we can see from Appendix 4 that the *s.e.* for species composition could be anything between 2% and 18%, and the *s.e.* for mean weight (for the dominant species) ranges between 4 g and 77 g. Figure 10 shows that the *s.e.* for A_{220} (mean age at the minimum legal size) could be as low as 0.3 y or as high as 1.6 y, depending on which stock is being sampled.

When the aim of the otolith sampling is to estimate A_W, the mean age at some target weight, W, there is a clear advantage to be gained by tailoring the sampling according to the value of W. The main consideration is that the distribution of weights of sampled eels should be spread approximately equally about W, rather than being skewed or off centre. This is illustrated in the right-hand panels of Figure 11, where, for $W = 220$, the equally spread U(200,240) is preferable to the skewed T(200,240) or the off-centre U(200,300). Theoretically, it doesn't matter how wide the distribution of weights is; so U(200,240) is no better than U(120,320). However, this is true only so long as the assumptions given above hold true. If, for example, the true relationship between age and log(weight) is not linear, then U(200,240) will be preferable to U(120,320). Thus it is prudent to keep the range of the target weight distribution as narrow as possible.

For areas (strata) where there were sufficient data, formulae have been provided to allow the optimisation of the design of future sampling programmes. For size and species composition, these are available for 14 strata (equation (1) with the coefficients in Table 5); for age, only five stocks are covered (equation (2) with the coefficients in Table 11). Of 28 catchments that have been sampled only 7 are represented in Table 5, and only 4 in Table 11. It may be possible to apply these formulae to other strata or stocks by analogy (e.g., use the coefficients from Table 5 for a stratum which is similar, in some sense, to the target stratum). Also, as more data become available these formulae can easily be developed for other areas using the above techniques.

It should be understood that these formulae can give only a rough guide to the precision that can be expected from a given sample design. In almost all strata the existing data are not extensive enough to give a precise picture of the extent of between- and within-landing variability. This is particularly true for the age data where no more than four landings per stratum could be used (Table 9). Note that although 4493 otoliths were collected in 1995–96 and 1996–97, data from only 649 of these were used in the age simulations because of the need to restrict to strata with at least 3 landings, and landings with at least 20 otoliths. To illustrate the fragility of the results in Figure 10, the simulations for Waikato stratum 1 longfin and A_{220} were repeated after discarding the data from landing 972502 (this corresponds to the most extreme of the points labelled 'A' in Figure 9A – *see* Table 9). The effect was, on average, to halve the estimated *s.e.*s in the top left panel of Figure 10. A further issue is that we know very little about year-to-year variability in catches from the same stratum because it was necessary to combine data from the sampling seasons in order to achieve adequate sample sizes (except in Mataura stratum 1).

Another potential weakness is that the above simulation experiments implicitly assume (because of the lack of specific information to the contrary) that the number of landings that is sampled from a stratum is only a small proportion of the total number for that stratum. If this assumption is badly wrong the *s.e.*s could be significantly over-estimated. However, this depends on how the results of the sampling programme are to be used. That is, whether the population about which inferences are to be made is just the actual catch, or the notional population of "available" eels in the stratum (i.e., the actual population filtered by some size-based selectivity function).

Despite these cautions the above formulae and coefficients are the best that can be inferred from the existing data and should provide a useful first step in optimising the design of future eel shed-sampling programmes.

Acknowledgments

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References

Beentjes, M.P. & Chisnall, B.L. 1997: Trends in size and species composition and distribution of commercial eel catches. *New Zealand Fisheries Data Report 89.*

Beentjes, M.P. & Chisnall, B.L. 1998: Size, age, and species composition of commercial eel catches from market sampling, 1996–97. *NIWA Technical Report 29.*

Draper, N.R. & Smith, H. 1981. Applied regression analysis. John Wiley and Sons, New York.

Appendix 1: Randomisation tests for differences between strata

In this Appendix the randomisation tests used for testing for differences in species composition and/or size between a pair of strata in Section 5.2 are described.

Suppose the data for one pair of strata come from m landings, and let the function S assign landings to strata, so that $S(l) = s$ means that landing l came from stratum s.

The test procedure follows 4 steps.

1. Calculate five statistics, $t_{1,1},\dots,t_{5,1}$, where $t_{1,1}$ is the absolute difference between the estimated values of %LFE for the two strata, and $t_{2,1},\dots,t_{5,1}$ are the corresponding absolute differences for L_{LFE}, L_{SFE}, W_{LFE} and W_{SFE}, respectively. Note that the estimates of %LFE, L_{LFE}, L_{SFE}, W_{LFE} and W_{SFE} used here are those for the entire catch, not just the random sample that was measured.

2. Generate a random permutation ϱ of the set $\{1,\dots,m\}$ (i.e., ϱ is a one-to-one mapping of this set onto itself). Now calculate the five statistics, $t_{1,2},\dots,t_{5,2}$, using exactly the same procedure as in step 1 except that the eels from landing l are now associated with stratum $S(\varrho(l))$.

3. Repeat step 2 a large number (N-2) of times using a different permutation each time and generating $t_{1,k},\dots,t_{5,k}$, for $k = 3,\dots,N$.

4. Calculate the proportions, $p_1,\dots,p_5$, where p_j is the proportion of the $t_{j,k}$ (for $k = 1,\dots,N$) for which $t_{j,k} \geq t_{j,1}$. The jth test is significant at the 5% level if and only if $p_j <$ 0.05.

Appendix 2: First simulation experiment: size and species composition

In this appendix I describe the process of simulating catch samples of eels (only size and species data are simulated – age data are considered elsewhere). Each set of simulations is based on data from a real catch sample that contains the following information. The data come from a series of m_0 landings, where n_i eels are measured at the ith landing, and

C_i = the weight (kg) of eels in the ith landing;
N_i = the (estimated) number of eels in the ith landing;
L_{ij} = the length (cm) of the jth eel in the sample from the ith landing;
W_{ij} = the weight (kg) of the jth eel in the sample from the ith landing; and
q_{ij} = a code specifying the species of the jth eel in the sample from the ith landing: 1 = longfin, 2 = shortfin.

Before simulating a catch sample we must specify

m_{land} = the number of simulated landings that are to be sampled, and
n_{eel} = the target number of eels to be measured from each landing (when the number of eels in a landing is less than n_{eel}, all are measured).

To simulate a catch sample the following steps are followed.

1. Pick two numbers, k_1, k_2, at random (with replacement) from $\{1,\ldots,m_0\}$. The first number determines the weight of eels in the simulated landing, C_k, and the second, the number of eels, n_{act}, that are measured (n_{act} is the lesser of n_{eel} and N_{k_2}).

2. The measurements (length, weight, species) of the n_{act} eels for this simulated landing are drawn from data for the k_2th real landing. This is achieved by picking n_{act} numbers at random (with replacement) from the set $\{1,\ldots,n_{k_2}\}$. If the jth of these numbers is i_j then the measurements of the jth fish in this sample are $L_{k_2 i_j}$, $W_{k_2 i_j}$, $q_{k_2 i_j}$.

3. Repeat steps 1 and 2 a total of m_{land} times to generate data for m_{land} simulated landings.

This procedure has been designed to produce, as much as possible, the same patterns of variation in the simulated samples as are found in the real data. It would have been simpler to set $k_1 = k_2$. However, this didn't seem necessary because it implies a correlation between landing size and either eel size or species composition, and such correlations did not appear to occur in the real data.

Appendix 3: Results from the first simulation experiment

Table 1: Estimated standard errors for species composition (%LFE) and mean size (L_{LFE}, L_{SFE}, W_{LFE}, W_{SFE}) as a function of number of landings sampled, m_{land}, and number of eels sampled per landing, n_{eel} for the 14 'strata' of Table 4. '*' = no shortfins in samples from this stratum; '-' = results not presented because species occurs in less than half the landings. Stratum codes: A = Mataura stratum 1 1995–96, B = Mataura stratum 1 1996–97, C = Mataura stratum 2, D = Mataura strata 3&4, E = Clutha stratum 1, F = Clutha stratum 2, G = Waitaki stratum 2, H = Waitaki stratum 3, I = Oreti strata 1&2, J = Oreti stratum 3, K = Aparima stratum 1, L = Te Waihora stratum 1, M = Te Waihora stratum 4, N = Waikato stratum 9

			Stratum													
	m_{land}	n_{eel}	A	B	C	D	E	F	G	H	I	J	K	L	M	N
%LFE																
	3	10	18.8	23.3	3.3	*	12.8	15.5	20.0	12.5	7.7	*	11.1	5.8	4.4	11.3
	3	20	18.9	22.5	2.8	*	12.5	14.9	18.7	12.3	7.7	*	9.6	6.8	3.8	10.1
	3	50	18.1	22.8	2.2	*	11.4	13.3	18.4	11.0	6.8	*	8.2	6.0	3.7	10.5
	3	100	18.0	22.2	2.0	*	11.1	13.3	18.1	10.8	6.4	*	7.8	6.5	3.5	9.4
	5	10	14.5	18.6	2.6	*	10.1	12.4	16.4	10.0	6.2	*	9.4	4.7	3.5	9.4
	5	20	14.8	17.8	2.2	*	10.1	11.7	15.6	9.6	5.8	*	7.3	5.2	3.0	8.9
	5	50	15.1	17.9	1.7	*	8.9	10.5	14.7	8.8	5.2	*	6.5	5.1	3.0	8.6
	5	100	14.2	17.5	1.6	*	9.2	10.4	14.4	8.6	5.0	*	6.2	5.2	2.9	8.2
	10	10	10.6	13.2	1.8	*	7.2	9.2	11.3	6.9	4.6	*	6.5	3.5	2.6	7.1
	10	20	10.6	12.9	1.6	*	7.4	8.4	11.0	6.6	4.3	*	5.2	3.6	2.3	6.6
	10	50	10.6	12.7	1.2	*	6.5	7.4	10.8	6.4	3.7	*	4.5	3.6	2.2	6.9
	10	100	10.4	12.9	1.1	*	6.5	7.5	10.9	6.1	3.5	*	4.2	3.6	2.0	6.4
	20	10	7.4	9.2	1.3	*	5.1	6.3	8.2	5.0	3.2	*	4.6	2.7	1.9	5.5
	20	20	7.4	9.2	1.1	*	5.1	6.0	8.0	4.6	3.1	*	3.9	2.6	1.7	4.9
	20	50	7.3	8.9	0.9	-	4.6	5.4	7.7	4.4	2.6	-	3.3	2.5	1.6	5.0
	20	100	7.5	9.4	0.8	-	4.7	5.4	8.0	4.3	2.5	-	3.1	2.4	1.5	5.0
L_{LFE}																
	3	10	1.3	1.3	1.9	3.0	1.2	1.7	2.3	2.2	1.3	1.3	1.2	-	-	-
	3	20	1.1	1.1	1.5	2.6	1.0	1.5	1.8	1.9	1.0	1.1	1.0	-	-	-
	3	50	0.9	0.9	1.2	2.5	0.8	1.3	1.6	1.6	0.9	1.0	0.9	-	-	-
	3	100	0.9	0.9	1.1	2.5	0.8	1.3	1.4	1.5	0.9	0.9	0.8	-	-	-
	5	10	1.0	1.0	1.5	2.4	0.9	1.3	1.7	1.7	1.0	1.0	1.0	-	-	-
	5	20	0.8	0.9	1.1	2.2	0.8	1.1	1.3	1.4	0.8	0.9	0.8	-	-	-
	5	50	0.7	0.7	0.9	1.9	0.7	1.0	1.1	1.2	0.7	0.8	0.7	-	-	-
	5	100	0.6	0.6	0.9	2.0	0.6	1.0	1.0	1.1	0.7	0.7	0.6	-	-	-
	10	10	0.7	0.7	1.0	1.6	0.7	0.9	1.2	1.2	0.7	0.7	0.7	-	-	-
	10	20	0.6	0.6	0.8	1.5	0.5	0.8	0.9	1.0	0.6	0.6	0.6	-	-	-
	10	50	0.5	0.5	0.7	1.3	0.5	0.7	0.8	0.9	0.5	0.5	0.5	-	-	-
	10	100	0.5	0.4	0.6	1.4	0.4	0.7	0.7	0.8	0.5	0.5	0.5	-	-	-
	20	10	0.5	0.5	0.7	1.2	0.5	0.6	0.8	0.9	0.5	0.5	0.5	-	-	-
	20	20	0.4	0.4	0.6	1.1	0.4	0.5	0.7	0.7	0.4	0.5	0.4	-	-	-
	20	50	0.4	0.3	0.5	0.9	0.3	0.5	0.5	0.6	0.4	0.4	0.3	-	-	-
	20	100	0.3	0.3	0.4	1.0	0.3	0.5	0.5	0.6	0.4	0.4	0.3	-	-	-
L_{SFE}																
	3	10	24.3	18.4	-	-	-	24.6	-	30.0	32.8	-	16.1	2.5	0.7	3.4
	3	20	19.0	14.8	-	-	-	19.1	-	22.6	28.3	-	9.7	2.4	0.4	3.2
	3	50	12.4	11.4	-	-	-	14.2	-	16.3	21.5	-	3.8	2.2	0.4	3.3
	3	100	10.4	9.2	-	-	-	9.6	-	15.3	15.1	-	3.4	2.1	0.3	3.2
	5	10	14.7	10.3	-	-	-	15.5	-	19.1	28.6	-	8.8	2.0	0.5	2.7
	5	20	10.0	7.3	-	-	-	8.3	-	13.5	19.9	-	4.3	1.9	0.3	2.5
	5	50	4.5	4.7	-	-	-	6.7	-	9.6	13.2	-	3.0	1.7	0.3	2.6
	5	100	3.5	3.0	-	-	-	5.0	-	8.4	7.2	-	2.7	1.6	0.3	2.6
	10	10	4.8	3.6	-	-	-	5.5	-	8.5	15.9	-	4.0	1.4	0.4	1.8
	10	20	2.4	1.8	-	-	-	3.2	-	6.6	8.9	-	2.8	1.3	0.2	1.8
	10	50	2.0	1.6	-	-	-	2.3	-	5.0	4.4	-	2.2	1.2	0.2	1.8
	10	100	1.9	1.4	-	-	-	2.4	-	5.1	3.3	-	1.9	1.2	0.2	1.8
	20	10	1.9	1.5	-	-	-	2.7	-	4.8	5.1	-	2.7	1.0	0.3	1.3
	20	20	1.6	1.2	-	-	-	2.0	-	4.0	4.0	-	2.0	0.9	0.2	1.3
	20	50	1.2	1.0	-	-	-	1.4	-	3.6	2.5	-	1.6	0.8	0.1	1.3
	20	100	1.2	0.9	-	-	-	1.1	-	3.5	2.0	-	1.3	0.9	0.1	1.3

Table 1, ctd.

	m_{land}	n_{eel}	Stratum A	B	C	D	E	F	G	H	I	J	K	L	M	N
W_{LFE}																
	3	10	41	38	71	126	29	48	83	73	35	44	34	-	-	-
	3	20	36	33	55	106	23	42	62	61	26	35	26	-	-	-
	3	50	30	26	47	102	19	36	55	52	23	29	19	-	-	-
	3	100	27	24	43	99	17	37	47	47	23	26	16	-	-	-
	5	10	31	29	56	97	23	36	60	57	27	33	25	-	-	-
	5	20	27	25	43	88	18	32	46	46	22	28	21	-	-	-
	5	50	23	20	35	77	15	27	38	39	18	22	15	-	-	-
	5	100	21	18	35	80	13	27	34	36	17	20	12	-	-	-
	10	10	23	20	37	68	16	25	43	41	19	24	17	-	-	-
	10	20	19	17	31	59	12	22	32	33	16	20	14	-	-	-
	10	50	16	14	26	53	10	19	26	28	13	16	11	-	-	-
	10	100	15	12	24	55	10	18	24	26	12	14	9	-	-	-
	20	10	16	14	27	49	11	17	28	29	13	17	13	-	-	-
	20	20	13	12	22	43	9	15	23	23	11	14	10	-	-	-
	20	50	11	10	18	37	7	14	18	19	9	10	8	-	-	-
	20	100	11	9	16	39	7	13	17	18	9	10	6	-	-	-
W_{SFE}																
	3	10	236	219	-	-	-	427	-	603	392	-	258	64	7	93
	3	20	190	195	-	-	-	355	-	513	349	-	181	60	6	88
	3	50	150	149	-	-	-	286	-	437	281	-	120	53	5	90
	3	100	131	135	-	-	-	235	-	411	233	-	101	49	5	89
	5	10	165	151	-	-	-	342	-	475	368	-	187	51	6	74
	5	20	128	115	-	-	-	255	-	376	282	-	132	48	5	67
	5	50	83	90	-	-	-	176	-	317	205	-	93	41	4	71
	5	100	71	76	-	-	-	170	-	310	154	-	80	38	4	70
	10	10	86	76	-	-	-	187	-	298	256	-	123	37	4	51
	10	20	61	60	-	-	-	130	-	257	174	-	89	33	3	50
	10	50	48	51	-	-	-	93	-	208	121	-	67	29	3	49
	10	100	42	45	-	-	-	101	-	209	101	-	57	28	3	49
	20	10	52	48	-	-	-	104	-	197	152	-	84	26	3	37
	20	20	40	39	-	-	-	80	-	167	110	-	63	24	2	36
	20	50	28	32	-	-	-	59	-	150	78	-	48	20	2	35
	20	100	27	30	-	-	-	52	-	146	64	-	40	20	2	37

Appendix 4: Second simulation experiment: age

In this appendix I describe the procedure used to obtain the simulated age samples described in Section 6.3. It was not possible to simply resample the data from the 1995–96 and 1996–97 catch samples, because when these were collected the aim was to obtain otoliths (and thus ages) from a wide range of eel sizes. Thus, these samples contain comparatively few otoliths from eels close to the target weights of 220 g and 500 g – insufficient for resampling. As an alternative, the following approach was taken.

It was assumed that the relationship between weight and age is given by

$$A_{ij} = \alpha_i + \beta_i \log(W_{ij}) + R_{ij}$$

where

A_{ij} = the age (y) of the jth eel in the otolith sample from the ith landing;
W_{ij} = the weight (g) of the jth eel in the otolith sample from the ith landing;
α_i and β_i are constants associated with the ith landing; and
R_{ij} is a residual which is independent of W_{ij} .

(Strictly speaking there should be a further subscript on all of the above symbols to denote species, but this has been suppressed here for convenience.)

The constants α_i and β_i were estimated, for each landing/species combination where there were sufficient data, by least-squares regression of age on log(weight), as outlined in Section 6.2. The estimated values are given in Table 9.

The assumption that the R_{ij} are independent of W_{ij} may not be strictly true. There appears to be a tendency for absolute residual size to increase with increasing eel weight. However, the data are not sufficient to estimate this trend well. Further, ignoring this trend doesn't seem likely to have a great effect on the results of these simulations. For these reasons the assumption of independence was allowed to stand.

There were three design variables for the simulated catch samples: m_{land}, the number of landings from which otoliths were sampled for a given stock; n_{oto}, the total number of otoliths that were sampled for that stock; and W_{dist}, the specified distribution from which eel weights were sampled. (As in the main text, we use the term "stock" here as a shorthand for a combination of species and stratum.)

The procedure for generating a simulated sample for a given stock was as follows.

1. A vector $\underline{w} = \{w_k, k = 1,...,n_{oto}\}$ of n_{oto} weights was selected at random from the distribution W_{dist} .

2. A vector $\underline{l} = \{l_i, i = 1,...,m_{land}\}$ of m_{land} landings was selected at random (with replacement) from all the landings for that stock in Table 9.

3. The n_{oto} otoliths were assigned to landings by randomly selecting a vector $\underline{L} = \{L_k, k = 1,...,n_{oto}\}$ of length n_{oto} from $\underline{l}$ (sampling with replacement). (Note that landings that occur more than once in $\underline{l}$ automatically have a commensurately higher probability of being selected at this step.)

4. A vector $\underline{r} = \{r_k, k = 1,...,n_{oto}\}$ of residuals was selected, with replacement, from the set of R_{ij} so that r_k was one of the residuals from landing L_k.

5. The age of the kth otolith in the sample was calculated as

$$a_k = \alpha_{L_k} + \beta_{L_k} \log(w_k) + r_k$$