REVIEW OF SOUTHERN BLUEFIN TUNA CATCH MONITORING PROCEDURES

CONDUCTED

BY

DSI CONSULTING PTY LTD

REPORT SUPPLIED

TO

SENIOR MANAGER TUNA AND BILLFISH FISHERIES, AUSTRALIAN FISHERIES MANAGEMENT AUTHORITY

REVIEW OF SOUTHERN BLUEFIN TUNA CATCH MONITORING PROCEDURES

Executive Summary

The Australian Fisheries Management Authority required the provision of consultancy services to review catch monitoring procedures used in the purse seine sector of the Southern Bluefin Tuna (SBT) fishery. They also requested recommendations on any necessary changes to these arrangements to improve the accounting of catch against allocated SBT Statutory Fishing Rights (SFRs).

The review was conducted over the period September 8th to November 29th 2005 in Canberra, Port Lincoln and Hobart. It consulted all relevant parties and received several written submissions.

Southern Bluefin Tuna are caught by purse-seiners in the Great Australian Bight and towed in cages to Port Lincoln where they are transferred to grow-out cages. The existing method of estimating the weight of the catch in each tow cage involves taking a sample of forty fish of at least ten kilograms from each tow cage, measuring their length and weight, and multiplying the average weight of the forty fish sample by the number of fish in the tow-cage determined by an underwater video count. A serious concern of several parties, and part of the terms of reference of the review, is the potential for bias in this method. Several parties consider that small fish are overrepresented in the forty fish samples and the total catch is underestimated as a result. While the review does not consider that the existing sampling method has been demonstrated statistically to be biased, there are some aspects of the forty fish samples, notably in the 2003/04 season, which are of concern. At this point in time the data does not exist to draw any conclusions about the issue of possible bias and the matter is still unresolved. Further data would need to be collected over several seasons to resolve this matter or a different method would need to be adopted.

The review is of the opinion that there are two viable methods of estimating the catch. The first, and the one to be used in the short term, is the existing method of a forty fish sample for fish over ten kilograms, combined with a video count of the total catch. If one is prepared to accept that the bias of the existing method has not been resolved one way or the other, then this method does reasonably well but could be made more precise by increasing the size of the sample. The review report presents tables of sample sizes needed to achieve specified levels of precision. It is noted that the present forty fish sample appears to strike a reasonable balance between precision and the practical constraints and risks of sampling at sea. The review also recommends some standardization in method of taking the forty fish sample including the use of standarised fishing gear.

However if there is a concern about the potential bias then it is not clear that the suggested modifications will resolve this concern. Increasing the sample size will not

correct the bias. Using AFMA catchers may remove any bias attributable to industry catchers, if such a bias exists. But it will do nothing about any differential propensity of fish to be hooked according to size.

The second method, which is called the “stereo linear method”, has three parts:

- The first component is a modified forty fish sample with fish under ten kilograms now included in the sample. A linear regression is fitted to the length and weight data from this sample. The number in the sample can be selected from provided tables to achieve a specified level of precision. The current forty fish will provide very accurate estimates;

- The second component is the length measurements of almost all fish in the tow cage obtained by stereo video cameras. This gives the average length of fish in the tow cage;

- The final component is a count of the number of fish in the tow cage obtained by an underwater video camera.

A simple formula combines the regression estimates with the average length and number of fish in the cage to give the stereo linear estimate of the total weight of fish in the cage.

This method can largely resolve the concerns raised about bias by some parties. However, there are two practical hurdles to be overcome before the stereo linear method is ready to be used for catch-weight estimation. The first is that the stereo video camera must be shown to be reliable, robust and simple to operate at all times at sea. The second is that the stereo video camera must be able to measure the length of almost all of the fish. At present, the hardware has not been shown to be sufficiently reliable, nor can it measure almost all of the fish, so it would be premature to adopt the stereo linear method at this time.

If the stereo video equipment has been shown to be reliable and breakdown free, the stereo linear method will offer advantages over the existing method. For a given sample size it will be more accurate than the existing method. It eliminates any bias in the existing method if small fish are more likely to be caught than larger fish on sampling. However it will incur additional costs.

Terms of Reference

1.

2. **Services**

2.1 The conduct of a review of catch monitoring arrangements and provision of recommendations to improve these catch monitoring arrangements for the purse seine sector of the Australian SBT Fishery.

2.2 The services will commence on 08/09/05 and terminate on the completion date.

2.3 The services to be provided will be delivered through consultation with all relevant parties including AFMA staff; AFMA's Port Lincoln contractor (Protec Marine Pty Ltd); SBT SFR holders, and relevant industry representatives; key SBT researchers and scientists; staff from the Department of Agriculture, Fisheries and Forestry; and State fisheries and compliance officers. A reasonable amount of consultation shall occur with the fore mentioned parties that shall not exceed 3 days in Port Lincoln. Minimal written submissions need be considered.

2.4 The contractor shall deliver a written evaluation report for initial consideration by SBT MAC by 30 September 2005, and by SBT MAC subsequently. The report shall be based on the terms of reference, namely to:

2.4.1 fully evaluate the methods and processes used to determine Australia's SBT purse seine fishery catch against allocated SFRs, taking into account AFMA's legislative objectives and the objectives of the SBT Management Plan;

2.4.2 consider methods and processes used to account for catch from the point at which SBT are taken by purse seine, through their transfer into tow cages, their subsequent tow to Port Lincoln and their transfer into grow-out cages, including the end of season audits;

2.4.3 identify any sources of bias - actual and potential - in the current sampling regime; and evaluate the precision, accuracy and statistical confidence levels of the current sampling process;

2.4.4 access and evaluate all relevant information;

2.4.5 provide a financial cost benefit analysis of all recommendations made; and

2.4.6 ensure that any recommendations are capable of providing a sampling regime that is unbiased, or can be corrected for any substantive biases; that can provide estimates of the surface fishery catch with the precision required to achieve 98%, 95%, 90% and 85% level of confidence, and is consistent with AFMA's legislative objectives including the need for efficient and cost-effective management arrangements.

2.5 The draft final report and final report shall be delivered to the Senior Manager Tuna and Billfish Fisheries, AFMA.

REVIEW OF SOUTHERN BLUEFIN TUNA CATCH MONITORING PROCEDURES

1. Introduction

Recent (2004) amendments to the Southern Bluefin Tuna (SBT) Fishery Management Plan 1995, require, among other matters, that the Australian Fisheries Management Authority (AFMA), as Manager of the Plan to

> *"evaluate, for each season, the mechanisms that have been put in place to monitor fishing catch against granted statutory fishing rights (SFRs) and Australia's national catch allocation for Southern Bluefin Tuna for that season, and implement any required changes for the following season (including whether the most appropriate technology has been used) and ensures that the results, including any recommendations for change, are publicly available for that season"* (section 4A.2f)

The measures taken will be assessed against performance criteria including

> *"that the mechanisms for monitoring fishing catch against granted statutory fishing rights and Australia's national catch allocation for Southern Bluefin Tuna for each season have been evaluated (including whether the most appropriate technology has been used) and the results, including any recommendations for change, are publicly available"* (section 4A.3d*)*

In recent years, 95-99% of Australia's national allocation has been taken in the surface fishery for Port Lincoln-based tuna farms. The SBT catch monitoring evaluation for the 2004/05 season was confined to the surface (purse seine) fishery.

1.1 Description of the study and its terms of reference

Pursuant to the above, AFMA required the provision of consultancy services to review catch monitoring procedures used in the purse seine sector of the Southern Bluefin Tuna (SBT) fishery and to recommend any necessary changes to these arrangements to improve the accounting of catch against allocated SBT Statutory Fishing Rights (SFRs). The terms of reference for this review are included at the beginning of this report. A three-person evaluation team was retained for the review, to be undertaken during the period commencing September 8th 2005, with a written report to be submitted to the Senior Manager, Tuna and Billfish Fisheries, AFMA.

The Terms of Reference note that

> *"The services to be provided will be delivered through consultation with all relevant parties including AFMA staff; AFMA's Port Lincoln contractor (Protec*

Marine Pty Ltd); SBT SFR holders, and relevant industry representatives; key SBT researchers and scientists; staff from the Department of Agriculture, Fisheries and Forestry; and State fisheries and compliance officers. A reasonable amount of consultation shall occur with the fore mentioned parties that shall not exceed 3 days in Port Lincoln. Minimal written submissions need be considered."

1.2 The management setting

The fishery for SBT is an international one, pursued throughout the temperate waters of the Southern Hemisphere, with Japan, Australia, Korea, Taiwan and New Zealand accounting for nearly all of the current global catch of around 16,000t. Most of the catch, or about 70%, comprises valuable adult fish taken by long-lining, with the remainder taken by purse seining in the Australian fishery, to supply grow-out farms.

The fishery has been managed since 1994 by the Commission for the Conservation of South Bluefin Tuna (CCSBT). In 2003, after a hiatus of several years, agreement was achieved amongst contracting CCSBT parties (Australian, Japan, New Zealand, Korea and Taiwan) on a global total allowable catch (TAC) of 14,030t, with national allocations of 5,265t for Australia, 6,065t for Japan, 1,140t for Korea, 1,140 for Taiwan and 420t for New Zealand, and nominal catch limits for non-parties of 800t for Indonesia, and 100t combined for Philippines and South Africa.

Australia's obligations to the CCSBT to manage, monitor and report on its national allocation are addressed under the Southern Bluefin Tuna Fishery Management Plan of 1995, amended in 2004, and managed by AFMA.

In the execution of Management Plans, AFMA has a responsibility to consult with all stakeholders on the fisheries resource when making management decisions. In this case, AFMA is advised by the Southern Bluefin Tuna Management Advisory Committee (SBT MAC).

1.3 The Australian Southern Bluefin Tuna Fishery

The Australian fishery for SBT initially developed as a pole-and-line fishery in NSW and South Australia in the 1950s, with more efficient purse seining following in the 1970s, to subsequently take most of the catch, destined at that time for canning. Catches peaked at 21,500t in 1982, but with a progressively reducing TAC and individual quotas for fishers after that time. Experimental tuna farming with transfer of live fish to cages for fattening and subsequent harvest began in 1990/91, and rapidly became very successful during the mid-1990s.

Since 1989, an informal and subsequently the CCSBT quota allocation for Australia of 5,265t has been in place. As noted earlier, 95-99% of Australia's national allocation, in recent years, has been taken in the surface fishery supplying Port Lincoln-based tuna farms, with most of the balance taken by long-line fishing vessels, which must hold a quantum of SBT quota according to the area fished.

The quota applies for the period December 1st to the 30th of November of the following year. Where the take exceeds the national allocation, as in 2002/03, the over-run is deducted from the following year's quota. Individual Statutory Fishing Rights (SFRs) make up the allocation, which are associated with a nominated vessel, and are transferable.

Fishing is mostly carried out along the edge of the continental shelf, in the Great Australian Bight, to the west of Port Lincoln, usually from December to March. Schools of SBT are located typically by spotter planes, and usually held by a pole-and-line vessel while the purse seine set is made. Fish are transferred to an associated tow cage after each set, with several sets usually required to fill the cage, around 9,000 fish in recent years. The tow cages are returned to the vicinity of Port Lincoln, with the tow, at less than one knot, often taking some weeks. Mortality in the cages en route is checked, recorded and dead fish removed. On arrival at the more sheltered approaches, a sample must be taken to obtain an average fish weight per tow cage. Also, a verified count of the numbers of SBT must be made during the transfer from tow cage to a series of grow-out cage, these typically holding 1,500-2,000 fish. There are approximately 40 tows made per year, involving around 300,000 fish in total.

After a grow-out period of usually 5-7 months, the fish are harvested for export, frozen or fresh, with a total turn-out of around 9,000t in recent years, worth in excess of A$250 million.

1.4 Current catch monitoring procedures

This review is only concerned with the purse seine sector of the Australian SBT fishery which accounts for 95-99% of Australia's national allocation. In that sector, the catch is monitored using two separate procedures. A sample of 40 fish with individual weights at least 10kg is obtained from each tow cage. An underwater video count is made of the number of live fish transferred from the tow cages to grow out cages. The total number of fish in the tow cage is obtained by adding the live fish count to the mortalities. The total weight is estimated as the product of the total fish and the average weight in the forty fish sample.

Both the fish counts and the weight sampling are carried out by a contractor, currently Protec Marine Pty. Ltd., as soon as practicable after arrival of the tow cage, and according to procedures set out in A.22b of the Southern Bluefin Tuna Fishery Management Plan 1995 as amended 2004.

The weight sample requires capture of fish by line or pole from the tow cage utilizing personnel and bait provided by the farmer, but under the supervision of the contractor. A sample of 40 fish greater than 10 kilograms in weight is taken, with any smaller fish excluded from the sample. Hooked fish are manouvered into aluminium cradles with the assistance of company divers, and hoisted inboard for weighing using a spring balance and length measuring, before release back into the cage. The management plan calls for weights to be recorded to two decimal points of a kilo. However in practice because of conditions at sea, individual fish weights are recorded to the nearest half kilo and the average of these weights is calculated to two decimal places.

The fish counts are made using an underwater video recording. The video camera is mounted to provide a side view of all fish passing from the tow cage into the grow-out cage. Both the transfer and the videos can be halted at any time, to ensure no fish are missed in the count due to technical failure. A rough manual count of the number of fish transferred can be made at the time, but the contractor, as an AFMA representative, and a farm representative must be present later to view the video record and reach an agreed tally of the number of fish.

A verified count is then produced, based on a total number of fish which is the agreed transfer count plus any mortalities since capture, multiplied by the average weight derived from the 40 fish sample. The management plan which provides clear guidelines associated with any variation associated with this procedure, has been in place since 2004.

A degree of independent audit of fish numbers, from capture to sale, is undertaken by SA Fisheries each year for several of the 12 farm companies now operating.

Few other approaches to estimating the weight of the catch have been trialed. An AFMA-funded trial of a stereo-video underwater system to measure individual fish lengths during transfers was conducted during 2003/04 as discussed in section 3. This could potentially be combined with a weight to length model to obtain weight estimates for the cages. Some parties have suggested a back projection method based on weights at harvest and estimated growth rates during the time in the grow-out cages.

Various parties have discussed possible biases and lack of precision in the current system. For example Robins and Huang in an undated confidential BRS working paper discuss the matter. Some possible sources of bias, inaccuracy and loss of precision in the current monitoring procedures are as follows:

- *Inaccurate estimates of mortality during capture and towing:* It has been suggested that the mortality associated with the catch may not be accurately recorded and that mortality is in fact greater than what is recorded. Suggested causes are practices during the actual catch, such as release, and damage to the fish and predation during transfer. One party suggested that very large mortalities may occur under some circumstances. It has not been suggested to the review that the numbers of fish mortalities reported are large enough to have a significant impact. Any unreported mortalities are largely a compliance issue, which may require the presence of more AFMA observers at the catch and during the tow;

- *Weight loss during towing:* It has been suggested that the fish may lose weight during the tow and consequently the weight estimate at time of transfer will be too low. However it has been pointed out that the companies now feed during the tow and the fish no longer lose weight during the tow as a result. In any case, no-one has suggested that it is feasible to do a weight sample and count from the tow cage in the catch zone since the sea conditions are quite difficult in the Bight. Other strategies, such as catching fish in the vicinity of the tow cage, would not provide suitable measurement data, since there is no guarantee that the fish would be representative of the fish in the tow cage;

- *Inaccurate weight estimates:* Sea conditions have dictated that weights are recorded to the nearest half kilo. The resulting errors in weights are almost certain to be unbiased;

- *Exclusion of fish smaller than 10 kilograms from the weight sample:* This will cause the average estimated weight to be higher than if these fish were included in the sample. This may be counter balanced by other factors. This will be considered at length in later sections;

- *Inadequate precision of overall weight estimates:* The review will consider the sample sizes necessary to obtain sufficiently precise estimates of catch.

- *Large fish underrepresented in samples:* It has been suggested by some parties that small fish are more likely than large fish to take the hook during the 40 fish sample. If this is true, then it would lead to an underestimate of the total catch. This issue will be considered at length in later sections;

- *Extra fish added after the count:* It has been suggested by one party that there is the possibility that extra fish could be added to the grow-out cages after the count. Although this may be possible, the review noted that there is a well documented audit processes in place which shows extremely close agreement between count and harvest numbers.

In section 2, the current 40 fish sampling scheme will be considered. Section 3 discusses the stereo video system for measuring fish lengths at transfer. Section 4 examines the use of a combination of a weight and length sample of about forty fish with stereo video measurement of the lengths of the complete tow cage to derive estimates of the total catch. Finally section 5 discusses the various options for estimating the catch-weight and makes recommendations for the future.

2. Assessing the 40-fish sampling scheme

2.1 General description

The current monitoring scheme has developed incrementally over a period of years. At present, the scheme requires information reporting in terms of SBT numbers, mortalities, weights and lengths in various forms and at various times. Specifically, the monitoring scheme encompasses the following stages:

- SBT are caught by purse seine and transferred to towing cages, at which time a rough estimate of total weight is made, as well as a count and estimate of weight for the mortalities during the transfer;

- Captured SBT are towed to Port Lincoln over a period of days or weeks, during which time the number of mortalities are recorded. It is during this period that the characteristics, for example weight and length, of the caught SBT may change;

- On approach to Port Lincoln, a sample of 40 SBT, excluding any with weights less than 10kg, is taken by hook from each tow cage and their weight and length, whenever possible, is recorded;

- On arrival in Port Lincoln, SBT in tow cages are transferred to farm cages. During this transfer, a video log is recorded for the purposes of enumerating the transferred SBT;

- The overall estimated total weight of each tow cage is then determined as the average weight of the sample of 40 SBT multiplied by the sum of the total number of SBT counted on the video transfer log and the reported number of mortalities from the time of capture until transfer to the farm.

2.2 Current accuracy and potential biases

The accuracy of an estimation procedure is the degree to which it provides an unbiased estimate of the quantity of interest. It should be noted that an unbiased estimate is not necessarily a precise one and may be highly variable, since it may be based on a relatively small amount of information. The accuracy of the current monitoring scheme depends on at least three key assumptions:

- The change in SBT characteristics, and in particular weight, during the period of towing is not substantial;

- The relative chance of any SBT being in the sample of size 40 is the same for all fish in the original catch in the tow cage, so that the sample is fully representative of the overall catch in the tow cage. In particular, this implies that there is no substantial differential according to size of the fish in the chance of either mortality during catch or transfer to towing cages or of “hooking” during the sampling process for SBT;

- The count of SBT per tow cage achieved by the current video monitoring is correct.

If these assumptions are valid, then the current monitoring methodology can be assumed to be unbiased. There seems little contention regarding the validity of the final assumption. However, the validity of the first two of these assumptions has been called into question. It has been suggested by some parties that there is a noticeable change in SBT characteristics over the period of towing. It has also been suggested by some other parties that the weight may increase over the tow period since most companies now feed fish during the tow. Without detailed research, involving at least collection of some weight information at the time of catch and detailing changes in characteristics of SBT during a period of towing, the extent of the potential bias created by these changes will be extremely difficult to quantify. It has also been suggested that conditions in the catch zone preclude measurement at the time of catch.

Regardless of whether there are changes to SBT characteristics during towing or not, the total weight estimate will still be an unbiased estimate of the total weight of SBT at the time of transfer to the farm, provided the second and third key assumptions remains valid. At least the second assumption cannot be exactly correct. Firstly, fish under 10kgs are excluded from the sample. The degree to which this requirement biases the overall weight estimate depends on the proportion of small fish in the tow cage. Using the information from the most recent two seasons, the actual average weight of a 40-fish sample can be compared to an estimate of the average weight of a 40-fish sample which included SBT under 10kg. Without reliable information regarding catch order, the estimated average for a 40-fish sample including SBT under 10kg must be calculated incorporating an inverse sampling or Haldane correction. The estimate is calculated as:

$$Estimated\ \ Average\,Weight = \left(\frac{40+n}{39+n}\right)\overline{X}_{All} - \left(\frac{1}{39+n}\right)\overline{X}_{40}$$

where $\overline{X}_{40}$ is the average from the actual 40-fish sample (i.e., excluding SBT under 10kg), $\overline{X}_{All}$ is the average weight of all fish sampled (i.e., including SBT under 10kg) and n is the number of SBT under 10kg that were caught during the sampling. Alternatively, this estimate can be calculated as:

$$Estimated\ \ Average\,Weight = \left(\frac{39}{39+n}\right)\overline{X}_{40} + \left(\frac{n}{39+n}\right)\overline{X}_{<10}$$

where $\overline{X}_{<10}$ is the average of the SBT under 10kg caught during the sampling process. The figures 1 and 2 below show the actual 40-fish sample average weight as well as the estimated average for a 40-fish sample including SBT under 10kg plotted against sample date.

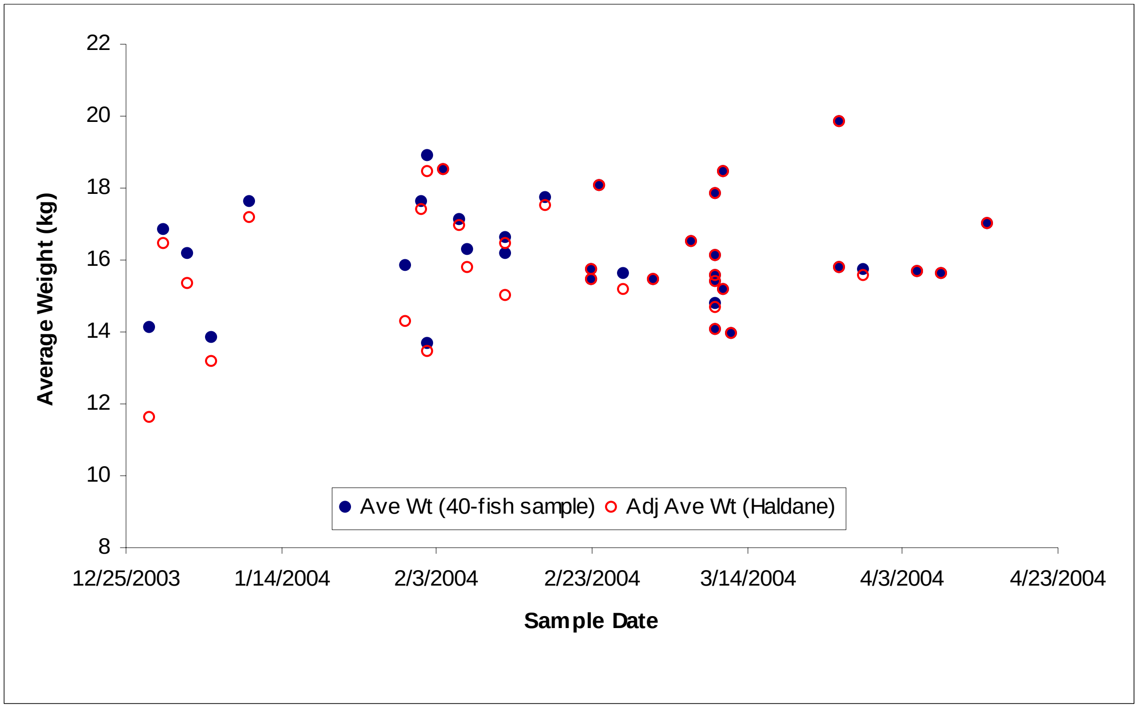

Figure 1: Average weight from 40-fish samples and adjusted average weight including SBT under 10kg by sample date for 36 tow cages in the 2003/04 season.

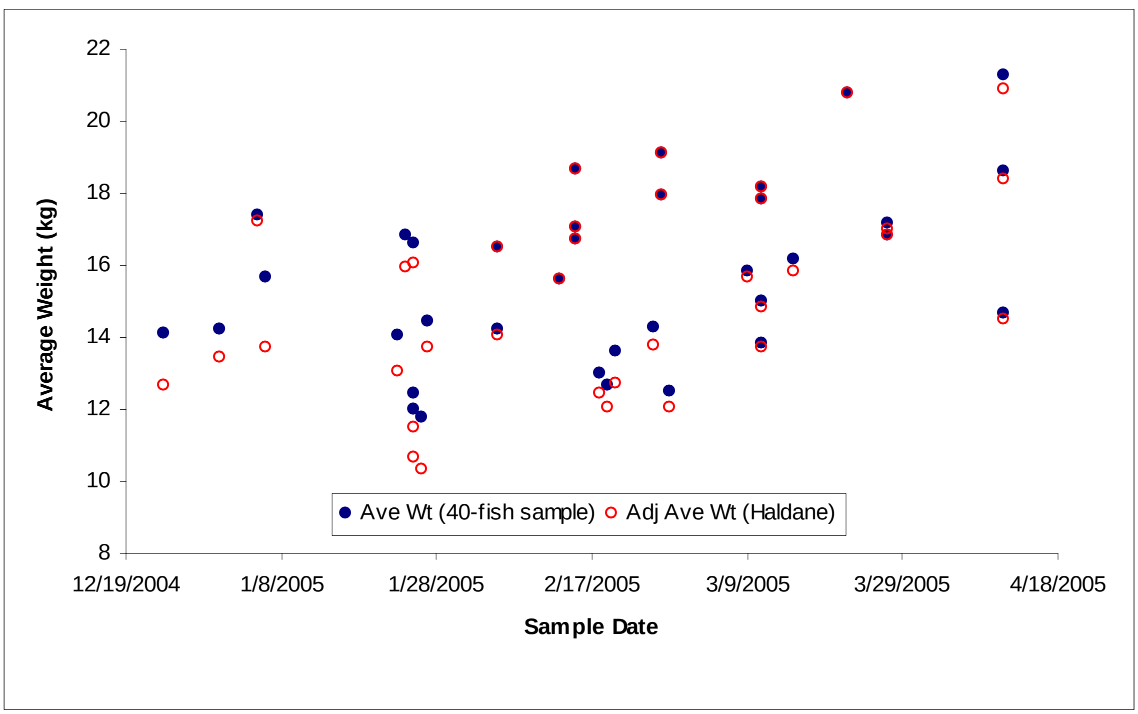

Figure 2: Average weight from 40-fish samples and adjusted average weight including SBT under 10kg by sample date for 36 tow cages in the 2004/05 season.

As can be seen, there are not many large differences between the two average weight estimates from each tow-cage. This indicates that those tow-cages in which a large number of SBT under 10kg were caught during the sampling process tend to have smaller SBT on the whole. Indeed, most of the noticeable differences between the two average weight estimates occur for tow-cages sampled early in the catching seasons, though there does appear to be a noticeably higher number of tow-cages late in the 2004/05 season with small SBT. The figures 3 and 4 below show the decrease in the number of SBT under 10kg sampled through the season. This clearly indicates the drop in the number of SBT under 10kg through the catching season, as well as the apparent increase in SBT under 10kg which were caught in the 2004/05 season.

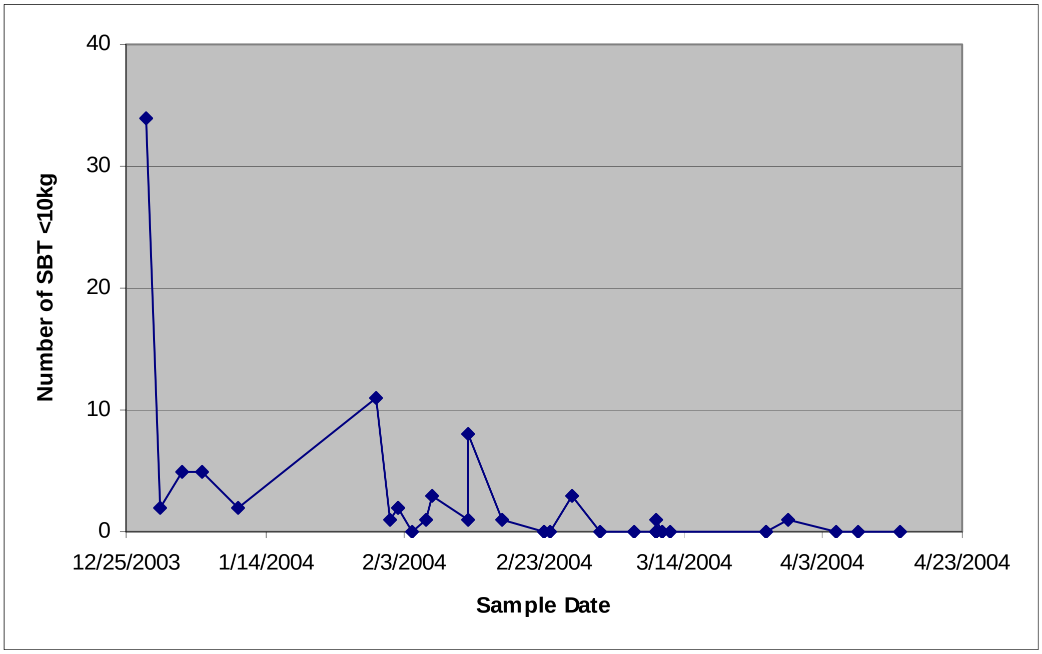

Figure 3: Number of SBT under 10kg in weight caught during the 40-fish sampling process by sample date for 36 tow cages in the 2003/04 season.

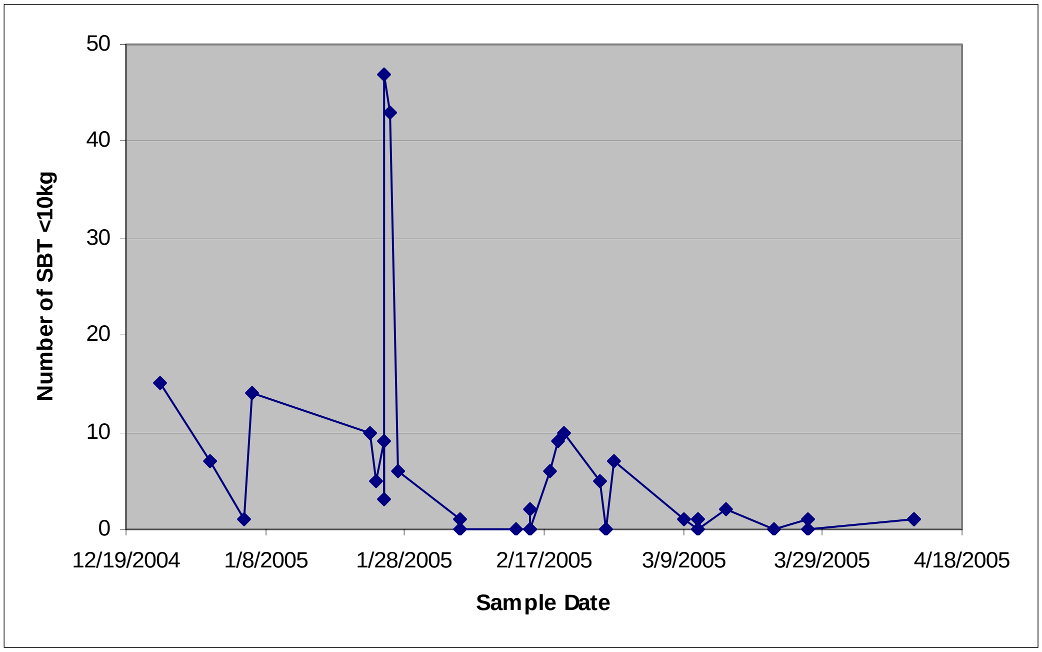

Figure 4: Number of SBT under 10kg in weight caught during the 40-fish sampling process by sample date for 36 tow cages in the 2004/05 season.

Of course, small changes in the estimated average weight may have a more substantial effect on the estimated total weight of SBT in an individual tow-cage. The table 1 below indicates the total fish counts and the changes in estimated total weights associated with the change in the average weight estimates for each of the 36 tow-cages from each of the 2003/04 and 2004/05 seasons. The change entry in table 1 is the change in estimated catch if the less than ten kilogram fish are included in the sample:

Cage Ref No.	2003/04 Season				2004/05 Season		
	Fish Count	Change in Total Weight Estimate (tonnes)	%Change in Weight Estimate		Fish Count	Change in Total Weight Estimate (tonnes)	%Change in Weight Estimate
1	8881	-21.77	-17.40%		9098	-13.20	-10.28%
2	7358	-3.00	-2.42%		10215	-8.12	-5.59%
3	8552	-7.25	-5.25%		11228	-2.22	-1.14%
4	8937	-5.60	-4.54%		9654	-18.60	-12.31%
5	8485	-3.56	-2.38%		11460	-11.84	-7.35%
6	7662	-11.71	-9.67%		8884	-7.79	-5.21%
7	6066	-1.31	-1.22%		9370	-4.64	-4.14%
8	6825	-3.21	-2.49%		11843	-6.42	-3.27%
9	7611	-1.64	-1.58%		12367	-21.78	-14.18%
10	11700	0.00	0.00%		13650	-19.79	-12.29%
11	12531	-2.39	-1.11%		7729	-5.52	-4.94%
12	9166	-4.65	-3.12%		7444	-0.87	-0.83%
13	12034	-2.29	-1.15%		9029	0.00	0.00%
14	10182	-12.22	-7.42%		8184	0.00	0.00%
15	8901	-1.94	-1.23%		7292	0.00	0.00%
16	6527	0.00	0.00%		9281	0.00	0.00%
17	7572	0.00	0.00%		10302	0.00	0.00%
18	7306	0.00	0.00%		7939	-4.38	-4.26%
19	9511	-4.26	-2.87%		10855	-6.83	-4.96%
20	5102	0.00	0.00%		10343	-9.45	-6.70%
21	8386	0.00	0.00%		12356	-6.74	-3.81%
22	4735	0.00	0.00%		6298	0.00	0.00%
23	5031	0.00	0.00%		7647	0.00	0.00%
24	4751	0.00	0.00%		13741	-6.62	-3.85%
25	3409	0.00	0.00%		5692	-0.90	-1.00%
26	5386	0.00	0.00%		8676	0.00	0.00%
27	8119	-0.99	-0.83%		7356	-0.80	-0.78%
28	11970	0.00	0.00%		10703	-1.74	-1.08%
29	10926	0.00	0.00%		11288	0.00	0.00%
30	10982	0.00	0.00%		7257	-2.36	-2.01%
31	9320	0.00	0.00%		7308	0.00	0.00%
32	8031	0.00	0.00%		12882	-2.47	-1.12%
33	8693	-1.35	-0.99%		5358	0.00	0.00%
34	12911	0.00	0.00%		8986	-2.04	-1.22%
35	7666	0.00	0.00%		6004	-2.14	-1.68%
36	7231	0.00	0.00%		8474	-1.73	-1.39%
Total	298456	-89.13	-1.83%		336193	-169.01	-3.24%

Table 1: Impact of 10 kilo rule on cage weight estimate

Overall, the effect of requiring SBT included in the 40-fish samples to be at least 10kg in weight results in an approximately 2-3% increase in the total weight estimate. However, the individual entries in the table show that this relatively small overall effect is not evenly spread across the individual tow-cages. Instead it has a larger effect for those tow-cages sampled earlier in the catching seasons (NOTE: the cage reference numbers are in the chronological order of sampling within the catching season).

It has been suggested by some parties that hand-line hooking of fish is not necessarily a reliable way to obtain a representative sample, since fish of different sizes have a differential propensity for being hooked. However, the results of the above table indicate that removing SBT under 10kg from the 40-fish samples to correct for this potential bias, is problematic. First, it clearly has a differential effect across the tow-cages with the early season catches receiving the greatest impact. Moreover, if the propensity for being hooked is related to SBT size, then even in cages where no SBT under 10kg are caught, there would still be a potential bias if smaller SBT are more likely to be sampled. It is conceivable that the current strategy of removing SBT under 10kg from the 40-fish samples corrects for the potential overall bias in the total catch weight estimate associated with the differential propensity for being sampled. However, it does not do so based on any reliable theoretical arguments. To more appropriately handle the potential bias due to differential sampling propensity, it would seem sensible to incorporate a methodology which can assess this differential sampling directly, and thus more accurately account for it. One possible method would incorporate length measurements using the stereo-video system, as described in section 3, and a model relating length to weight, perhaps based on the 40-fish sample from each tow-cage, to accurately account for the differential sampling propensity of SBT of varying sizes. This strategy will be discussed in section 4.

2.3 Sample size and precision

The precision of an estimate is the degree to which it gives “repeatable” answers in separate sampling instances, and reflects the variation in the estimation and sampling procedure. It should be noted that a very precise estimate may still be biased, in which case the estimation procedure will produce values which differ consistently from the value of interest by the bias. In general, the precision of an estimation procedure is tied most directly to its sample size. However, other factors may also influence the precision of an estimator, including the structure of the sampling scheme.

The current monitoring scheme to estimate total catch-weight can be viewed as a stratified sampling scheme, since a sample of 40 fish is taken from each of the tow cages. Simple calculations show that, assuming that the sample of 40 fish is reasonably representative of the entire population of the tow cage, and is obtained as a simple random sample, the precision of the catch-weight estimate within a single tow cage is

$$\text{Precision for Cage } i = \sqrt{\frac{N_i^2(N_i - 40)}{40(N_i - 1)}\sigma_i^2}$$

where N_i is the number of SBT in the i^{th} tow cage and σ_i^2 is the variance of the weights of the SBT in the i^{th} tow cage. Moreover, the precision of the total catch-weight estimate is then easily seen to be:

$$\text{Precision for total catch-weight} = \sqrt{\sum_{i=1}^{C}\frac{N_i^2(N_i - 40)}{40(N_i - 1)}\sigma_i^2}$$

where C is the total number of tow cages for the season.

Information provided indicates that in the 2003/04 and 2004/05 seasons, there were 36 tow cages totaling 298,456 and 336,193 SBT, respectively, including mortalities, which led to overall catch-weight estimates of 4,860 tonnes in the 2003/04 season and 5,215 tonnes in the 2004/05 seasons. The following table 2 shows the total fish counts per tow cage, as well as the estimated standard deviation of weights within each cage (i.e. an estimate of σ_i), a 95% confidence limit for the estimated catch weight within each tow cage expressed as a percentage of the catch-weight estimate for the corresponding tow cage and the sample size required to obtain a 95% confidence limit for the total tow-cage catch weight equivalent to 5% of the catch-weight estimate.

Cage Ref No.	2003/04 Season					2004/05 Season			
	Fish Count	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 5% of Catch-Weight		Fish Count	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 5% of Catch-Weight
1	8881	3.40	9.04%	129		9098	3.64	8.89%	125
2	7358	3.15	5.91%	56		10215	3.65	8.41%	112
3	8552	3.70	7.46%	89		11228	3.38	6.07%	59
4	8937	3.35	7.86%	98		9654	4.42	9.96%	157
5	8485	3.11	5.59%	50		11460	3.93	9.32%	138
6	7662	4.01	8.69%	119		8884	4.35	8.45%	113
7	6066	2.73	4.85%	38		9370	2.48	6.68%	71
8	6825	2.85	4.77%	36		11843	3.97	7.65%	93
9	7611	3.12	7.16%	82		12367	2.46	7.15%	81
10	11700	3.21	5.38%	46		13650	2.15	6.42%	66
11	12531	3.08	5.62%	50		7729	3.91	8.81%	123
12	9166	3.40	6.67%	71		7444	3.56	7.82%	97
13	12034	2.96	5.57%	50		9029	3.66	6.87%	75
14	10182	4.09	8.45%	114		8184	4.65	9.21%	134
15	8901	2.20	3.89%	24		7292	2.41	3.98%	25
16	6527	3.60	7.20%	82		9281	4.64	8.58%	117
17	7572	3.12	6.13%	60		10302	3.32	6.02%	58
18	7306	3.26	5.58%	50		7939	2.90	7.21%	83
19	9511	3.46	7.06%	79		10855	2.79	7.17%	82
20	5102	3.42	6.84%	74		10343	3.76	9.14%	133
21	8386	3.59	6.72%	72		12356	3.77	8.47%	114
22	4735	3.75	7.20%	82		6298	2.40	3.88%	24
23	5031	3.38	6.70%	71		7647	3.49	6.02%	58
24	4751	3.86	6.69%	71		13741	2.45	6.29%	63
25	3409	2.68	5.87%	55		5692	3.71	7.32%	85
26	5386	2.71	5.43%	47		8676	4.00	6.93%	77
27	8119	3.66	7.72%	95		7356	3.62	8.16%	106
28	11970	2.99	6.10%	59		10703	4.26	8.88%	125
29	10926	3.66	6.14%	60		11288	4.47	7.61%	92
30	10982	2.98	6.61%	70		7257	4.72	9.21%	134
31	9320	3.28	5.11%	42		7308	5.40	8.02%	102
32	8031	3.67	7.19%	82		12882	4.44	8.08%	104
33	8693	3.32	6.61%	70		5358	5.23	9.59%	144
34	12911	3.28	6.48%	67		8986	5.26	8.85%	124
35	7666	3.16	6.25%	62		6004	10.15	14.99%	341
36	7231	3.22	5.86%	55		8474	4.04	8.63%	118

Table 2: Individual tow cage statistics

The table 2 entries indicate that at the 95% level of confidence, the precision of the catch-weight estimates within individual tow-cages are on the order of 5-10% of the catch-weight. In addition, the sample size required to achieve a 95% confidence limit equivalent to 5% of the total catch-weight varies between 24 and 129, with an average of 68 for the 2003/04 season and between 24 and 341, with an average of 104 for the 2004/05 season. In order to adjust the sample size required to achieve a 95% confidence limit equivalent to 2.5%, that is half of the value used in constructing the table, the sample size values listed in the table should be essentially quadrupled, while to achieve a

95% confidence limit equivalent to 1%, the sample size values should be multiplied by a factor of 25. The precision estimates for the most recent season show a degradation from the previous season, which is primarily due to the greater variation in SBT weights within tow cages. The standard deviations for the previous season range from 2.20kg to 4.09kg, while those for the most recent season range from 2.15kg to as high as 10.15kg. Also note that, per the discussions in the preceding section, these precision estimates, and those in the following tables, are based on the adjusted average weight and the observed standard deviations from the complete 40-fish samples, that is including any SBT under 10kg collected from each tow cage. As noted in the previous section, the restriction on sampling SBT of at least 10kg will have a differential effect on the accuracy of estimates within individual tow-cages. The sampling scheme restrictions will also have an effect on precision estimates. In particular, the restriction on SBT under 10kg will tend to decrease the observed standard deviation of the sampled SBT, meaning that precision and sample size calculations based on the actual 40-fish sample values will tend to overstate the precision, and thus understate the required sample sizes to achieve particular precision levels.

While the precision levels for individual tow-cages are typically on the order of 5-10% of the catch-weight, the overall precision for total catch-weight is much better. The following table 3 shows the precision for the overall catch-weight estimate from the 2003/04 and 2004/05 seasons:

Confidence Level	2003/04 Season			2004/05 Season	
	Confidence Limit (in tonnes)	Percentage of Estimate		Confidence Limit (in tonnes)	Percentage of Estimate
98%	62.7	1.31%		81.7	1.62%
95%	52.7	1.10%		68.7	1.36%
90%	44.2	0.93%		57.7	1.14%
85%	38.7	0.81%		50.5	1.00%

Table 3: Overall catch statistics

Further, in order to achieve confidence limits of either 1% or 0.5% of the total catch-weight estimates, the required sample size of SBT per tow cage are given in table 4 below:

Confidence Level	2003/04 Season			2004/05 Season	
	Sample Size for Confidence Limit of 0.5%	Sample Size for Confidence Limit of 1%		Sample Size for Confidence Limit of 0.5%	Sample Size for Confidence Limit of 1%
98%	269	69		403	104
95%	192	49		289	74
90%	136	34		205	52
85%	105	26		158	40

Table 4: Sample size requirements for overall catch precision

Again, we see that the precisions for the most recent season are lower than those for the previous season. In particular, we note the large range of variations in SBT weights within tow cages for the most recent season, as well as the variation in the number of SBT per cage. In these circumstances, it should be noted that the relative precision of the estimation procedure based on a given total sample size, that is the total number of SBT sampled over all tow cages, which currently stands at 40 times the number of cages, can be increased by varying the sample allocation. The general principles involved indicate that sample allocation across tow cages should be proportional to the number of SBT in the cage and the variation of SBT weights in the cage. In other words, cages with larger numbers of SBT or with a larger variation in SBT weights should be allocated a larger number of sampled SBT.

As an example of the extent to which allocating sample size according to changing variation in weights from cage to cage may effect precision, note that the total sample of SBT during the 2004/05 season was 36 lots of 40 fish, or 1440 fish. Suppose we retain the same total number of sample SBT, but reallocate the samples non-uniformly over the 36 tow-cages so that the sample in each cage is proportional to the total SBT times the standard deviation of weights. Then we would allocate a sample sizes ranging from 18 for cage 22 (which had the second lowest standard deviation of SBT weights of 2.40kg and the fourth lowest number of SBT in any tow-cage of 6,298), up to 68 for cage 35 (which had, by far, the largest standard deviation of SBT weights of 10.15kg). If these allocations were implemented, than the 95% confidence limit would reduce from 1.36% to 1.31% of the total catch-weight estimate, while the 98% confidence limit would reduce from 1.62% to 1.56% of the total catch-weight estimate. Of course, actual implementation of such a scheme would require knowledge of all the cage counts and variations at the outset, and thus may be impractical. However, it is conceivable that increases in precision can be gained by over-sampling from tow cages which are thought to have a relative high number of fish or a relatively high variation in weights. The increase in efficiency of such an approach will rarely be substantial, but can be noticeable if the variation in SBT numbers and/or SBT weight variations are substantial, as appears to be the case for the most recent season.

2.4 Issues and discussion

As noted above, the precision of the total catch-weight estimate under the 40-fish sampling scheme is quite good. Of course, at the level of individual tow-cages, the precision is lower, and if precise catch-weight estimates for single cages are desired, then much larger samples per cage will be required. Alternatively, the precision of catch-weight estimates at the level of companies will depend on the number of tow cages associated with each company. The precision will also depend on the specifics of the associated tow-cages, including their total fish counts and variation in weights. However, in general, the precision of a catch-weight estimate for an aggregation of tow-cages will generally improve with the square-root of the number of cages. For example, if a company has four tow-cages, each with individual 95% confidence limits which are on the order of 5% of the catch-weight within the cage, then the 95% confidence limit for the company catch-weight, that is the total of the catch-weights within the four cages, will be essentially half of the value for the individual cages, namely 2.5%. This general relationship persists for the total catch-weight, where we see that individual tow-cages have 95% confidence limits generally on the order of 6% of the catch-weight, and thus the total catch-weight estimate for the aggregation of all 36 tow-cages has a 95% confidence limit equal to one-sixth of the value for an individual tow-cage, namely, a value on the order of 1%. Finally, it should be noted that precision for total catch-weight estimates will generally be much higher than that of distribution estimates, for example length distributions, based on samples of the same size. If precisions for length distribution estimates comparable to those currently achieved for the total catch-weight estimates are required, then much larger samples will be needed, perhaps collected via the stereo-video system. For more information, see section 3 on length distribution estimation and use of stereo-video system for size measurements.

The precision calculations depend on the assumption of random sampling and may be impacted by departures from that assumption, such as over or under dispersion. Any impact would very likely be quite minor at the overall season level. There is no directly relevant data available which allows this issue to be addressed.

While precision is quite good, the accuracy of the total-catch weight estimates relies upon two key assumptions, both of which are, perhaps, questionable. First, as noted previously, there appears to be varying opinions regarding the assumption that the catch-weight of SBT does not change substantially during the period between catch and transfer to farm cages. If this assumption is not correct, then any catch-weight estimate which does not appropriately account for changes in SBT weight during towing will be biased. Of course, the size of this potential bias depends on the degree to which SBT weights change during towing. While there appears to be various opinion regarding growth rates and weight change parameters of SBT in varying conditions, it is impossible to assess the potential size of any bias associated with such changes without direct measurements of changes during an actual towing operation.

By contrast, the potential bias associated with differential sampling propensities can be assessed and appropriately accounted for, provided sufficiently detailed length measurements for a large proportion of SBT in a tow-cage are available. This could be through the use of the stereo-video system for size measurements as described in section 3 and an adequate model relating lengths and weights. Assuming that length distributions within a tow-cage can be accurately and precisely measured, adjustment of catch-weight estimates can be performed using an appropriate model relating SBT weight to SBT length. One possibility would be to develop a single, global model which relates weight to length. Geometric arguments suggest that a power regression, which relates SBT weight to a power of SBT length as:

$$Weight = \alpha(Length)^{\beta}(1 + error)$$

However, the plot in figure 5 of weights versus lengths for the data from the 1,512 SBT sampled during the 40-fish samples of the 2003/04 season and the 1,608 SBT sampled during the 40-fish samples of the 2004/05 season for which length measurements were available shows that a simple linear relationship, which relates SBT weight directly to SBT length as:

$$Weight = \alpha + \beta(Length) + error$$

may be satisfactory. The power regression has an overall R^2 of 95.6%, while the linear regression has an overall R^2 of 94.8%. The distinction between the two models is not of much importance overall. However, further investigation reveals that the relationship between SBT length and SBT weight varies significantly across the tow-cages which is, at least in part, due to the variation in catch dates and timings during the growth cycles of the SBT population. Interestingly, if we allow separate power relationships to be estimated for each tow-cage, then the predicted weights of a 90cm SBT for each cage is shown in the figure 6 below, and we see that as the catch date progresses, the estimated weight of a 90cm SBT tends to decrease. The main conclusions to draw from this plot are that the relationship between weight and length do vary from cage to cage across a season (though the relative pattern of this change is consistent across seasons, as indicated by the two superimposed LOWESS trend lines in the estimated weight for a 90cm SBT for each season) and that the “steepness” of the relationship decreases throughout the season. Thus in the early tow-cages, increases in length translate to larger increases in weight than corresponding increases in length for SBT in the later tow-cages. Regardless of the specifics of the relationship, the strong indication is that, if length-to-weight relationships are used to estimate SBT weights, that they be estimated on a tow-cage specific basis.

The next section considers the use of the stereo video system to give more complete information about the length distribution of fish in the tow cages.

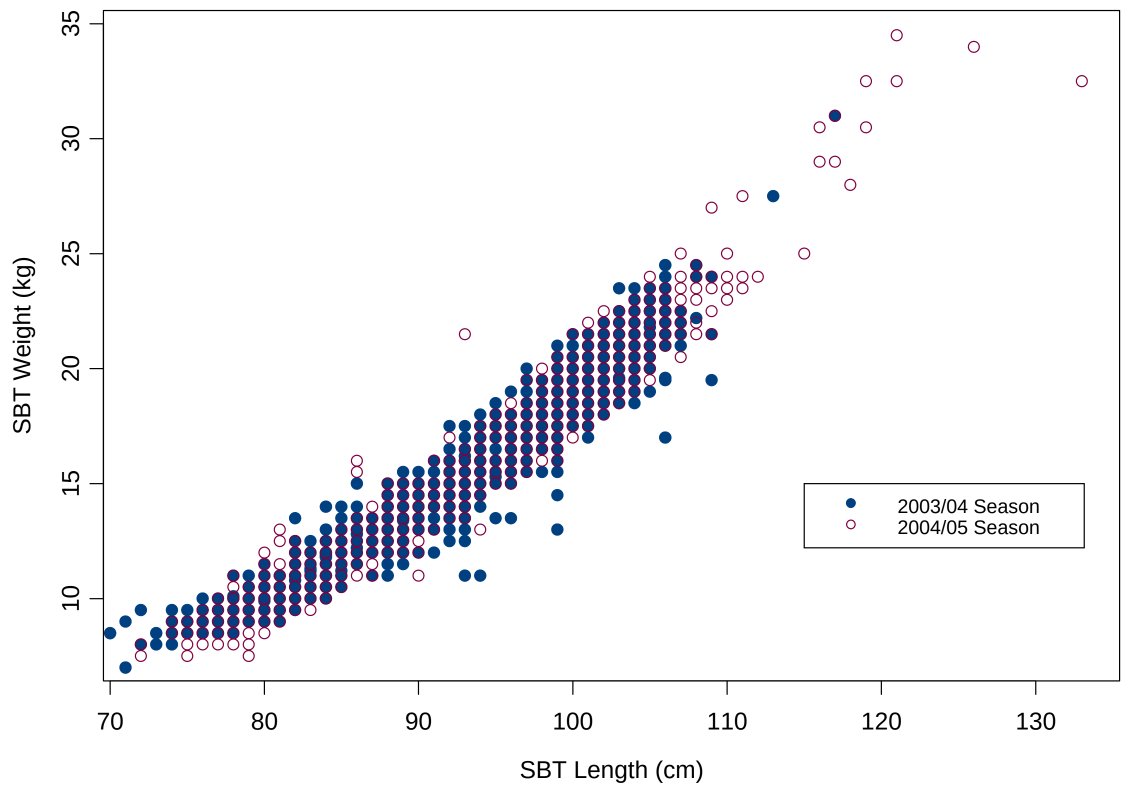

Figure 5: Plot of SBT Length versus SBT Weight for the 2003/04 and 2004/05 Season 40-fish samples.

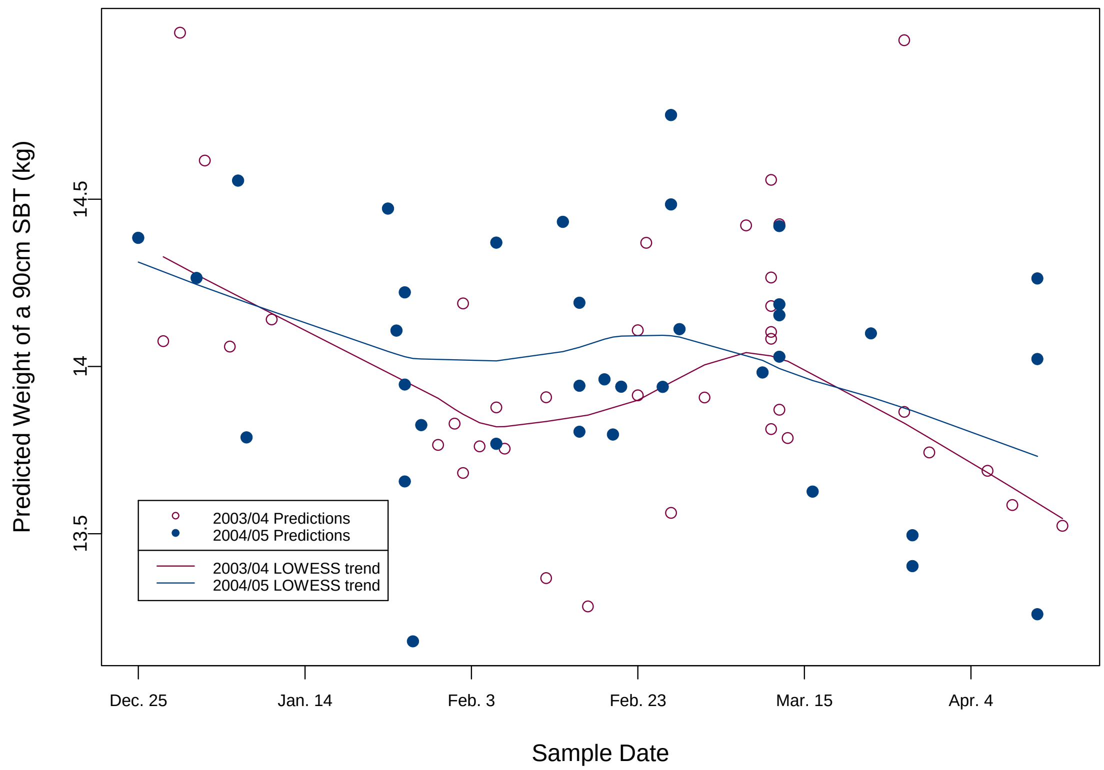

Figure 6: Predicted weight of a 90cm SBT from the 36 tow-cages in each of the 2003/04 and 2004/05 seasons, using separate power relationships for each cage.

3. Using stereo-video cameras to measure SBT sizes during transfer

3.1 Introduction

In an effort to investigate alternative methodologies for determining SBT size distributions, AFMA funded a research program into the potential for the use of underwater stereo-video cameras to measure SBT snout to fork lengths (SNFL) and maximum body depths (MBD) during transfer from tow cages to grow-out cages. One notable advantage of this methodology is that it is non-intrusive. Health dangers to SBT as a result of either hooking or handling during a manual sampling and measuring procedure may be reduced, or even avoided altogether.

The primary objectives of the AFMA-funded research program were to:

- investigate the feasibility of using an underwater stereo-video system to measure the size of SBT during transfers to farm cages and to develop an appropriate measurement protocol;

- assess the accuracy and precision of size measurements under realistic transfer conditions on actual caught SBT;

- familiarise representatives of the fin-fish aquaculture industry, management agencies and research organisations with the use of stereo-video systems as well as develop user-friendly interfaces to allow the system to be routinely and easily implemented during transfers.

The stereo-video camera apparatus is relatively simple, consisting of two joined high-definition cameras connected to a computer for digital recording and storage of images. The AFMA-funded research project indicated that essentially the same time and effort in set-up and recording were required for the stereo-video cameras as for the currently employed video system for manually counting SBT during transfers to grow-out cages. The stereo-video cameras require an initial calibration, but once the calibration has been done, deployment and use parallels the efforts currently undertaken. Of course, with the more advanced technology associated with the stereo-video cameras, it must be expected that on-going maintenance, including periodic checks of the calibration, and upgrades will be required on a regular basis, and appropriate time and funding must be set aside for this if long-term implementation is to be instituted.

The measurement of SBT is typically performed manually using recorded transfer images to identify key features of each SBT. A trained operator must select these features, for example the nose and tail of the SBT in the case of SNFL measurement, on a computer screen image of a sequence of synchronised images using a computer mouse. Appropriate software then provides an estimated measurement. In order to ensure appropriate accuracy of the measurement, it is critical that the right and left images, from the two cameras of the apparatus, are properly synchronised and that the selection of key features is correctly matched in both of the synchronised images. Synchronisation is readily achieved via time-coding or other similar mechanisms. However, manual operator matching of key features in the synchronised images was identified as a primary source of measurement error. Finally, it is important that the measurement be made on an image of an SBT where the body is oriented at no more than 60 degrees away from the cameras and relatively straight, so as to avoid distortion due to “flexing” during swimming.

3.2 Counting and automation

As noted previously, the current fish count is performed via a marine video camera recording viewed manually by an operator. The stereo-video system will yield an equivalent mechanism for manual counts, provided that the entire relevant period of transfer is recorded, that is the periods when SBT are actually swimming into the farm cage. Given the issues associated with operator errors in identifying matched key features in the synchronised video images, some effort may be warranted to develop an automated system for measuring sizes which avoids the need for manual determination of key features. It may be argued that, if successful, this automated process for determining size measurements may also substitute as an automated fish count mechanism.

In order for this substitution to be implemented, however, it must be ensured that all SBT may be automatically measured, or at least registered for measurement. In the 2003/04 season, experimenters (Harvey et al 2005), in a trial of the stereo-video system, were given permission to measure fish from five tow cages which were subsequently shown to contain a total of 38183 fish. In the live trials of the stereo-video system it was not possible to measure the sizes of all SBT during a transfer. Equipment breakdown also prevented the measurements of several transfers. The transfers that could not be monitored because of equipment failure contained 15609 fish. In the remaining transfers of 22,574 fish (as determined by manual video count), only 19,690 (87.2%) could be measured. The remaining 2,884 SBT could not be measured for a variety of reasons:

- 920 (4.1%) were partially obscured by another SBT, a diver or a net;
- 978 (4.3%) swam through the field of the cameras too quickly to provide an appropriate image where the SBT was entirely in the image frame and sufficiently straight;
- 986 (4.4%) had image clarity or brightness issues severe enough to prevent operator determination of key features.

The 87.2% success rate in measurement during monitored transfers represented a small increase from an 83.2% success rate in an earlier trial on 672 SBT measurements. The remaining SBT could not be measured, mainly due to partial obscuring of key features. Even if image quality and frame capture rate issues can be completely resolved, Harvey et al (2005) comments that is unlikely that more than 90-95% of SBT can be manually measured, and automated length measurement will probably reduce this figure. Furthermore, as noted previously, the transfers monitored were only a subset of the transfers from the five tow cages, with camera breakdown being a primary reason for the failure to monitor the remaining transfers. The total number of fish in the five tow cages was 38183, so the stereo video system was only able to measure 19690 out of 38183 fish or 51.57%. The system failed to measure 40.88% because of equipment failure and the remaining 7.55% for the technical reasons described above. As such, using the stereo-video length measurements as a substitute for the complete manual fish count has not been demonstrated to be practically feasible at this time. Furthermore, because of equipment failure and technical issues, it has not been demonstrated that length measurements can be obtained for more than about 50% of fish in the tow cages. Any proposed monitoring technique which requires significantly more than 50% of the fish to be length measured has not been proven at sea at this time. However, combined with a complete manual fish count, the stereo-video size measurements may provide useful auxiliary information which may improve the accuracy of the overall catch weight estimate as well as providing information regarding the length distribution of the catch which may in turn give important information relating to stock management.

3.3 Accuracy and precision

In order for the stereo-video measurements to provide useful auxiliary information for catch-weight determination as well as useful information for length distribution determination, their precision and accuracy, whether determined by manual or automated procedures, must be validated.

Validation of the stereo-video accuracy and precision was a primary objective of the AFMA-funded research program. The errors in SNFL and MBD measurements were determined in various experimental situations as well as for live SBT in a research pen.

In a controlled environment, measuring two immobile plastic silhouettes of length 853mm and 454mm, the reported overall accuracy decreased with distance. It was determined that beyond a range of 5 metres, the accuracy of the length measurements was unacceptably low. At a range of 2 metres, the accuracy of the manual length measurements of the silhouettes had a mean error of approximately –2mm, while at a range of 4 metres, the mean error was approximately –7mm. Overall, for ranges between 2 and 4 metres, the mean error of manual length measurements of fixed plastic silhouettes was –2.31mm.

Accuracy and precision of the stereo-video system for measuring live SBT in the field is lower than for fixed plastic silhouettes due to a range of issues including:

- Motion of objects may tend to blur edges on images, making key feature detection more difficult;
- “Flexing” of SBT during swimming will tend to distort body length;
- Objects oriented at large oblique angles to the cameras will not be measured accurately.

At least two separate trials to assess the accuracy and precision of the stereo-video system on live SBT have been performed at research pens operated by the South Australian Research and Development Institute (SARDI). The more recent of these trials, and thus presumably the more relevant, based on 25 individual SBT, showed that the mean error for SNFL measurements based on a single image of each SBT was 2.7mm, or 0.27% relative error, with an approximate standard deviation of 9.2mm. The range of individual errors was from –32.16mm to 25.93mm, or –2.94% to 2.44% relative errors. In the other trial, 81 SBT were recorded, from which 47 had SNFL and MBD measurements taken and a further 7 had only SNFL measurements taken. The remaining measurements were unable to be made due to diver or bait-fish obscuring of the individual SBT key features. The measurements for the 47 fish are plotted in figure 7. For the 54 SNFL measurements, an average error of 1.72mm, and average relative error of 0.16%, was observed with a standard deviation of 8.13mm, and standard deviation of relative error of 0.76%. For the 47 MBD measurements, an average error of 1.37mm, and average relative error of 0.51%, was observed with a standard deviation of 5.06mm, and standard deviation of relative error of 1.78%. In neither case is the average error or average relative error statistically significantly different from zero. In other words, the size measurements using the stereo-video system are essentially unbiased. However, their precision is on the order of 5-10mm, or one-half to three-quarters of a percent for relative errors. This issue must be addressed if the measurements are to be used in any subsequent calculations of either catch weights or length distributions. Moreover, for the earlier trial, where errors on both SNFL and MBD were available, it can be seen that the errors are moderately correlated. The correlations were $r = 0.241$ and a p-value = 0.103 for absolute errors shown in the figure 7 below and $r = 0.279$, p-value = 0.058 for relative errors. This observed correlation may be a result of the fact that image quality and SBT orientation to the cameras are a notable source of error in the stereo-video system. These would affect both dimensional measurements of a given SBT similarly.

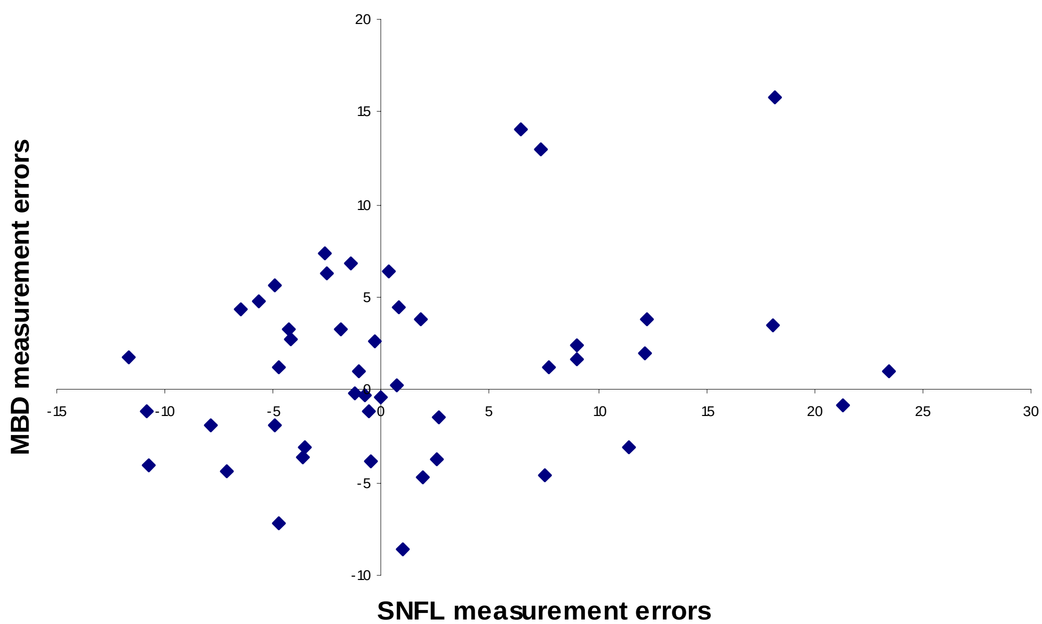

Figure 7: Plot of SNFL versus MBD measurement errors for 47 SBT.

In order to increase the precision of the size measurements, the average of values determined from a number sequential images of the same SBT were taken. Increasing the number of repeated measurements for each SBT increases the precision of the measurement as well as the time taken to complete the measurement process. As such, the degree of increased precision must be assessed against the increases in time necessary to undertake the measurements. The actual transfers from tow cages to farm cages involves tens of thousands of SBT, and small time increases in the measurement process per SBT translate to significant time increases in the overall measurement procedure. The initial trial of 81 SBT field measurements included a trial of repeated measurements on 10 of these SBT. It indicated that precision appeared to be optimised with 5 repeated measurements. Subsequently, in the trial of 25 SBT field measurements, where improved technology was available, the average of either 2 or 3 sequential measurements appeared to be an optimal trade-off between time and increased precision. However practical requirements to measure all fish may dictate that one measurement per fish is appropriate.

As noted previously, one of the primary sources of error in the stereo-video measurements arises from operator inaccuracy in targeting key features on the paired images of the recorded transfers. One possible approach to reducing this component of error is to implement an automated image matching function using epipolar line searching. A trial of this approach was conducted to investigate the potential advantages and disadvantages. It appears that the image matching and manual approaches produce very similar results. The manual approach appears slightly more accurate with smaller mean errors, but slightly less precise with larger standard deviation of errors. Automated approaches may eventually provide significant time savings in length measurements, particularly for the large numbers of SBT recorded during actual transfers. However at present there does not seem to be significant accuracy advantages to implementing an automated measurement approach. Of course, ultimately, the financial cost of an automated system may eventually be lower and lead to its adoption.

In general, the trials demonstrated that the stereo-video system provided measurements which had high accuracy, and also high precision. Finally, it should be noted that the assessment of accuracy and precision from these trials is based on small numbers of SBT. It is possible that, with the extreme increase in the number of measurements made from recordings of actual SBT transfers, the accuracy and, particularly, the precision of measurements may well decrease.

3.4 Issues and discussion

If the stereo-video system is to be implemented for size measurement of SBT at the time of transfer from tow-cages to farm cages, there are various issues which should be addressed.

3.4.1 Bias associated with unmeasured fish

As noted above, experience thus far is that all of the transferred SBT have not been measured. This gives rise to the potential for bias in the assessment of length characteristics of the transferred population of SBT, if there are consistent tendencies for SBT of a particular size to be unmeasured. Obscuring by other SBT and swim speed are two key aspects which determine whether a given SBT can be measured. If these aspects are also related to SBT length, then there will be a bias in the measured distribution of lengths. For example, if longer SBT are more likely to be partially obscured, or if they tend to be faster swimmers, then there will be a bias in the measured length distribution towards shorter SBT. The potential for this bias to noticeably affect length distributions will also depend on the actual proportion of SBT which can be measured. As the proportion of measured fish approaches 90% or more of the SBT from a transfer, then the potential for large biases associated with the unmeasured SBT is likely to be low. However, if less than 90% of the SBT are measured, then the potential for length bias in the measurements becomes more substantial.

3.4.2 Number of SBT to be measured

It is unlikely that all of transferred SBT will be able to be measured. This raises the question of whether a subset of SBT should be chosen for measurement, rather than simply measuring all SBT for which measurement is possible. Clearly measuring a subset may save significant time and money. If the subset is representative of the distribution of the lengths within the tow-cage, then the distribution estimates will be unbiased. However they will be less precise than if all SBT were measured. Of course, the method of deciding which SBT to measure will be critical in determining whether the resultant sample is representative. Note that, even if SBT are selected randomly from amongst those possible to measure, the resultant sample will only be representative of the group of measurable SBT. Thus the potential bias noted above is still relevant and the proportion of SBT which are measurable will determine the extent of the possible effect of this bias. An investigation of the number of SBT (Harvey et al, 2005) which should be measured to ensure precision of a specified level was conducted during the AFMA funded projects associated with the assessment of the stereo-video system. The conclusion reached was that a number of SBT equal to 796, plus one-third of the number of SBT transferred, should be sampled from each tow-cage. In the opinion of the review, these sample size numbers should be applied with extreme caution and only if samples are a truly random sample of the whole tow cage. A further discussion of this analysis is provided in subsection 3.4.3.

3.4.3 Sample size recommendations for stereo video measuring

The conclusions reached on recommended sample sizes for stereo video measuring depend on the assumption that the tuna samples are drawn randomly without replacement from a tuna population of interest. The data presented in Harvey et al (2005) does not support that conclusion for the estimation of the length distribution of tow cages. Indeed there is clear evidence of substantial differences in mean lengths over transfers. In figures

6, 7 and 8 of Harvey et al (2005), it is very clear that there are very significant differences in mean lengths between transfers and that individual transfers may have very different length distributions from the length distribution of the full tow cage. The paper notes that these differences do not appear to occur in any particular order and concludes that SBT lengths will need to be collected from each transfer to obtain a representative sample of length measurements. In fact, the data suggests that sub-samples which consist of all fish which pass through the cameras in a fixed window of time cannot be regarded as a random sample of tuna in the cage. Complete enumeration is required for stereo video measurement to be useful for estimating the length distribution in the tow cage.

The sample size recommendations in the paper concerning the significance of the Kolmogorov Smirnov Statistic are based on the assumption that the random sample is randomly selected from the target population. Certainly, it is clear that the transfers are not random samples from the whole tow cage and therefore neither are the fish measured by video transfer. So the Kolmogorov Smirnov Statistic should not be used for statistical inference about the whole tow cages from the fish measured in Harvey et al (2005). Furthermore, in light of the evident transfer level effect, it is plausible that there may be length clumping within the transfers and that the statistical inference may be questionable for the transfers as well. In some sense the problem addressed in the paper is not relevant to the issues at hand. It poses the question that if it was possible to get a truly random sample from the tow cage, then how large should that sample be to get suitably close to the true distribution in the cage? Since the evidence is that the sequential transfer of lots does not yield a random sample, the sample size recommendations are not relevant to the data in Harvey et al (2005), in the opinion of the review. The only way it may possibly be relevant is if there was a complete record of all transfers available and fish could be selected completely at random from that record for measurement. This may save processing time, but since the indications are that it is possible that the measurement process will be automated, it is difficult to see that this will be an important issue. Consequently it is likely that the derived significance levels based on a subset of transfers are invalid for inference about the whole tow cage and should not be relied upon as a guide for the required sample size for the whole cage length distributions. In other words, estimates of mean lengths based on sub-samples may be inaccurate estimates of the mean length of the cage.

To further investigate this issue, Kolmogorov-Smirnov Statistics were calculated to compare transfers within the same tow cages. Under the assumption that the transfers are random samples from the tow cages, we would expect that the Kolmogorov Smirnov tests should not detect any differences between the transfers. If differences are detected, then that is strong evidence that the transfers cannot be regarded as representative of the length distribution in the complete tow cage and that any statistical inference which is based on that assumption is suspect. Table 5 gives the p values of the Kolmogorov Smirnov Statistics. In ten of the comparisons, the p values are essentially zero, with another two of .0019 and .0384. In only one case, the comparison of transfers 2 and 3 in tow cage 4, does the Kolmogorov Smirnov Statistics fail to detect a difference between transfers within the same tow. The conclusion is that individual transfer data cannot be relied upon to make inference about the length distribution in the whole cage. Indeed that would still be the case if for example four out of five transfers were measured and for example 80% of the fish in the cage. The existing data shows that it is feasible that the remaining 20% of fish in the tow cage could be very different from the fish that were measured. The differences in length distribution can be seen further in figure 8 where the cumulative distribution functions of the length distributions are plotted for each of the transfers within the tow cages. The tendency of the fish to clump in lengths could be further investigated by time series methods, but more information on the fish that were not counted within each transfer would be desirable before that analysis was performed.

Cage	Transfer Pair	Sample sizes	Kolmogorov-Smirnov Test *p*-value
1	1 & 2	1271 & 1564	0.0019
2	1 & 2	1778 & 1209	0
	1 & 3	1778 & 2750	0
	1 & 4	1778 & 617	0
	2 & 3	1209 & 2750	0
	2 & 4	1209 & 617	0
	3 & 4	2750 & 617	0
4	1 & 2	1246 & 1487	0
	1 & 3	1246 & 171	0
	2 & 3	1487 & 171	0.5754
5	1 & 2	2274 & 1894	0
	1 & 3	2274 & 2367	0
	2 & 3	1894 & 2367	0.0384

Table 5: Kolmogorov Smirnov Statistics for comparing length distributions between transfers within tow cages

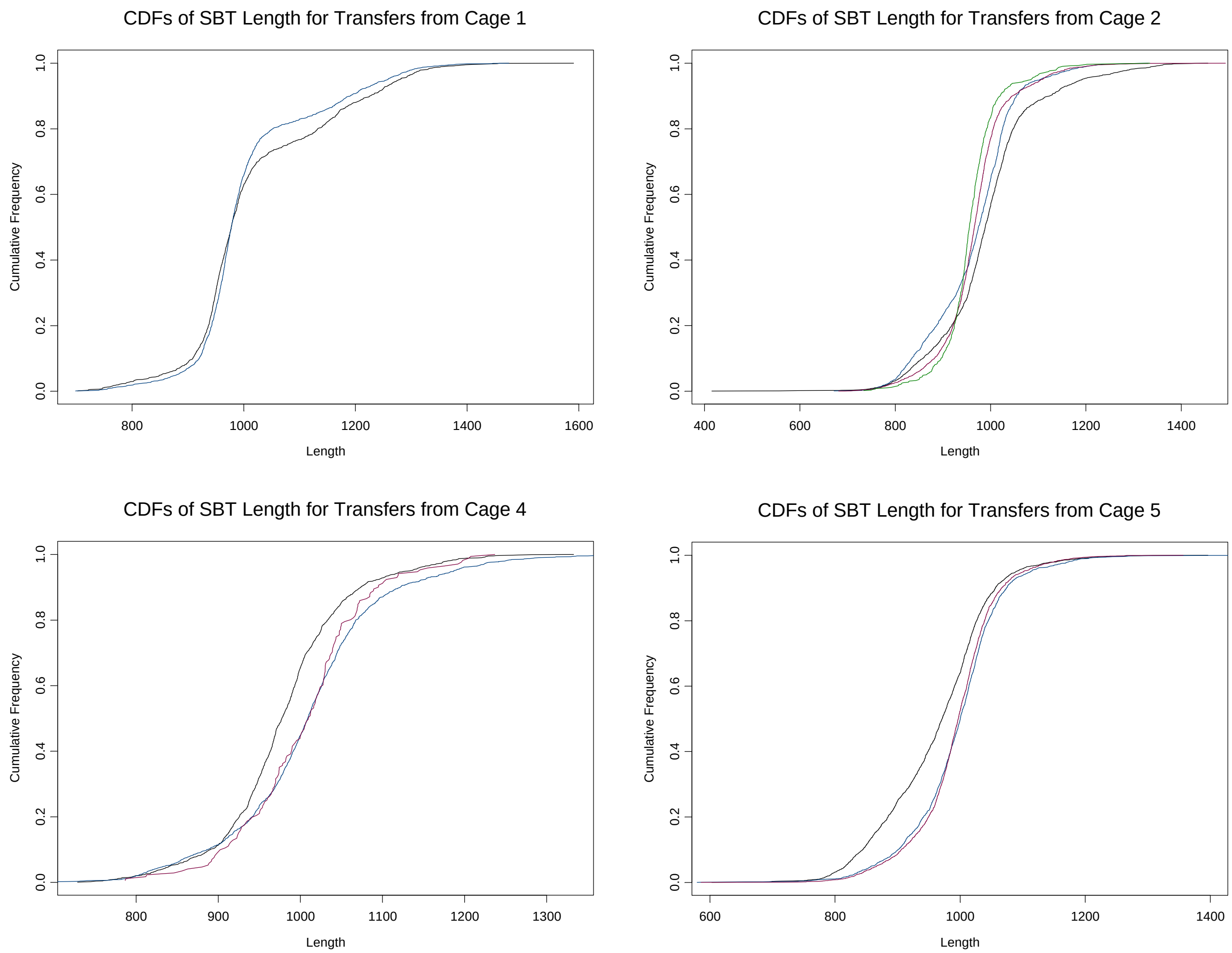

Figure 8: Cumulative distributions of lengths for transfers within tow cages

3.4.4 Using size measurements to model SBT weight

The current catch weight per tow-cage assessment is based on a sample of 40 SBT with weights at least 10kg. It has been suggested by some parties that this approach is not sufficiently accurate and is biased because small fish are more likely to be in the sample. It is possible to improve both the accuracy and precision of the catch weight estimate based on the 40-fish sample without increasing the size of the sample of hooked SBT by using the length distribution of SBT within the tow-cage. The stereo video system has the potential to estimate, without bias, the length distribution within tow cages. In order for this improvement to be applied, a reasonably reliable model is required relating SBT length, and possibly MBD, to SBT weight. Since it is likely that this relationship is season and sample dependent, it is unlikely that a single, overall model of size to weight will be sufficient. Tow-cage specific models will need to be constructed, and these can be based on the 40-fish sample, provided the hooked SBT are all measured for length as well as weighed. A more detailed discussion of this approach and its potential benefits and precision improvements are given in section 4 of this report. It should be noted, however, that any use of predicted weights based on SBT size measurements made using the stereo-video system should take into account the precision of these measurements.

3.4.5 The Bureau of Rural Sciences submissions

The Bureau of Rural Sciences made two submissions to the review. One is a paper, called the BRS paper subsequently, titled “Stereo-video cameras show bias in southern bluefin tuna (Thunnus Maccoyii) size sampling in South Australian aquaculture farms”, and the other submission is a powerpoint document, titled “Bias in southern bluefin tuna monitoring”, describing the results of the paper. In brief, the BRS paper compares the length distribution of the 2003/04 tuna measured by stereo video to the length distributions of the 40 fish samples from the same cages. The conclusion in the BRS paper is that the lengths of the forty fish samples measured in the individual transfers are shorter by 2.5 centimeters on average than those measured in the 40 fish samples. It is then assumed that this also applies to the full tow cages and this is mapped using a length weight key to infer that the weights are underestimated by 8 to 10% using the 40 fish sample. However, in view of the evident clear differences between length distributions in transfers from the same cage, as discussed in section 3.4.3, it is the opinion of the review that these conclusions cannot be made on a sound statistical basis. It is important to note that, as discussed in section 3.2, the 19690 fish which are the subject of the BRS paper are a subset out of 22574 fish involved in the transfers which were measured. However, the 22574 fish were a subset of the 38183 live fish in the 5 tow cages. The remaining fish were in transfers that could not be measured because of equipment failure. It is important to remember that the tow cages and transfers which were measured were not randomly selected and it cannot be argued retrospectively that the data came from an acceptable sampling scheme. Since there is no certainty that the measured transfers are representative of the full tow cages, the significance values and minimum sample sizes reported in Table 1 of Harvey et al (2005) are not relevant to inference concerning the full cages. This is the opinion of the review.

Although the statistical case for bias in the forty fish sample has not been established by the BRS submissions, nevertheless there is one matter for concern. There are large fish present in the stereo video measured fish whereas there are no large fish in the 40 fish samples in the 2003/04 season. The complete absence of large fish in the 40 fish samples in the 2003/04 season would lend credence to the argument advanced by some parties that small fish have greater propensity to be caught in the forty fish sample and as a result imply a bias in the forty fish sample. However, the situation is not so clear in the 2004/05 season. There were some noticeable differences in the size of SBT sampled from the 2003/04 season to the 2004/05 season. In particular, the number of larger SBT sampled in the most recent season is noticeably higher than it was in the preceding season. The following table 6 details the number of SBT in the 40-fish samples from the two seasons of particular lengths and weights. It is clear that the phenomenom where large fish were not hooked in the 2003/04 season did not occur in the 2004/05 season. The contrast is made even stronger by the fact that in 2004/05 there were six fish over 20kg for which the length measurement was missing, including the four largest SBT sampled, and that overall fish were smaller in the 2004/05 season. This suggests that even if the conclusions reached in the BRS submissions had a sound statistical basis, their relevance to other seasons would not be clear and it may well be that the 2003/04 season was an anomaly. To investigate this matter further it would be necessary to examine the 40 fish sample data over several seasons.

The use of stereo video measurement of lengths combined with a length weight relationship to estimate weight of the catch in the tow cages will be discussed further in section 4.

	SBT Length Measurements among 40-fish Samples				SBT Weight Measurements among 40-fish Samples			
Season	Total*	> 100cm	> 110cm	> 120cm	Total	> 20kg	> 30kg	>40kg
2003/04	1512	315	2	0	1523	163	1	0
2004/05	1608	384	16	4	1649	233	12	4

* Not all sampled SBT had length measurements. This primarily occurred among the SBT under 10kg in weight; however, in 2004/05 there were six fish over 20kg for which length measurements were missing, including the 4 largest SBT sampled.

Table 6: Size statistics for 40-fish samples

4. Estimating total catch-weight using length-to-weight relationships

4.1 Introduction

As noted at the end of the section 2 on assessing the accuracy of the 40-fish sampling scheme for estimating total catch-weights, the potential differential propensity to be included in the 40-fish sample for SBT of varying sizes can be overcome by appropriate application of “regression estimation”. The method suggested in this section requires an accurate and precise estimate of the relationship between SBT length and weight as well as the average length of SBT in a tow-cage. We investigate regression modeling of the length-to-weight relationship and use this to develop more accurate and precise total catch-weight estimates. We note, however, that the new estimation methods do not alleviate the need for a sample of SBT from each tow-cage. Rather they use the information gained from the sample of fish in conjunction with additional length information, to arrive at more accurate and precise estimates.

4.2 Modeling length-to-weight relationships

A single global model for relating SBT length to weight does not seem appropriate since the variation in the relationships between tow-cages can be significant. Individual regression models for each tow-cage should be employed. For each of the 2003/04 and 2004/05 seasons, two model forms were considered for the individual relationships between SBT length and weight, the simple linear form

$$Weight = \alpha + \beta(Length) + error$$

and the power regression form

$$Weight = \alpha(Length)^{\beta}(1 + error)\,.$$

These models were fitted to the SBT from the 40-fish samples from each tow-cage. The associated parameter estimates, including error variation, and R^2 values, as well as the average weight and length of the SBT in the 40-fish sample, are shown in the tables 7 and 8 below:

Cage Ref	AveL (cm)	AveW (kg)	Simple Linear Regression				Power Regression			
			α	β	σ	R^2	$\alpha x10^4$	β	σ	R^2
2003/04 Season										
1	93.0	16.5	-19.91	0.39	0.72	0.949	2.47	2.45	0.043	0.965
2	97.2	17.4	-27.36	0.46	1.22	0.810	0.38	2.85	0.075	0.831
3	98.4	17.5	-29.12	0.47	0.75	0.886	0.18	3.00	0.044	0.913
4	93.3	15.7	-25.77	0.45	0.78	0.939	0.75	2.70	0.051	0.940
5	98.2	18.4	-33.22	0.53	0.92	0.939	0.13	3.08	0.052	0.949
6	93.6	15.8	-28.04	0.47	0.99	0.930	0.38	2.85	0.064	0.929
7	99.3	18.5	-34.42	0.53	1.28	0.845	0.29	2.91	0.066	0.863
8	96.2	17.0	-27.30	0.46	0.77	0.940	0.40	2.83	0.042	0.959
9	94.0	16.5	-28.07	0.47	1.13	0.904	0.57	2.77	0.064	0.920
10	93.8	16.1	-28.21	0.47	1.15	0.908	0.45	2.81	0.072	0.911
11	88.5	13.7	-19.55	0.38	0.73	0.943	2.71	2.41	0.050	0.949
12	99.1	18.4	-29.59	0.48	0.93	0.895	0.20	2.98	0.050	0.930
13	92.8	15.4	-26.66	0.45	0.79	0.953	0.47	2.80	0.051	0.957
14	93.0	15.4	-25.54	0.44	0.69	0.960	0.63	2.74	0.042	0.968
15	89.0	14.1	-18.40	0.36	1.28	0.777	5.87	2.24	0.094	0.748
16	92.8	15.4	-23.26	0.42	0.92	0.889	1.49	2.55	0.058	0.899
17	91.5	15.3	-26.92	0.46	0.90	0.911	0.69	2.72	0.063	0.894
18	91.6	15.0	-24.93	0.44	0.90	0.953	0.43	2.82	0.061	0.958
19	92.9	15.2	-27.81	0.46	0.87	0.938	0.26	2.92	0.051	0.956
20	91.7	15.6	-29.03	0.49	0.64	0.965	0.44	2.82	0.038	0.968
21	96.9	17.8	-30.60	0.50	1.01	0.933	0.33	2.89	0.057	0.943
22	89.9	14.0	-27.78	0.46	0.71	0.944	0.29	2.90	0.048	0.945
23	93.3	15.6	-31.06	0.50	0.71	0.956	0.18	3.01	0.048	0.951
24	93.9	15.7	-27.28	0.46	0.85	0.934	0.38	2.84	0.055	0.939
25	94.2	15.6	-27.72	0.46	0.71	0.951	0.57	2.75	0.045	0.949
26	97.0	17.0	-30.35	0.49	0.94	0.916	0.31	2.89	0.052	0.933
27	82.6	11.7	-17.67	0.36	0.79	0.947	2.27	2.45	0.065	0.946
28	91.3	15.5	-25.42	0.45	0.84	0.946	0.37	2.86	0.057	0.952
29	90.4	14.3	-25.47	0.44	0.82	0.959	0.30	2.90	0.051	0.971
30	87.8	13.5	-25.76	0.45	0.73	0.947	0.31	2.90	0.057	0.938
31	94.8	16.1	-24.70	0.43	0.83	0.933	0.57	2.76	0.053	0.943
32	97.0	18.1	-31.00	0.51	0.85	0.934	0.29	2.91	0.047	0.946
33	91.4	14.7	-25.56	0.44	0.74	0.960	0.85	2.67	0.044	0.966
34	99.8	19.8	-29.84	0.50	0.88	0.929	1.08	2.63	0.041	0.948
35	97.0	17.6	-33.04	0.52	0.83	0.898	0.43	2.82	0.041	0.917
36	96.3	16.4	-28.35	0.47	0.81	0.927	0.31	2.88	0.045	0.948

NOTE: Average weights presented here are determined from only those SBT sampled which had length measurements and thus could be included in the regression analyses.

Table 7: Tow cage regression estimates for length-weight relationship for 2003/04

Cage Ref	AveL (cm)	AveW (kg)	Simple Linear Regression				Power Regression			
			α	β	σ	R^2	$\alpha x10^4$	β	σ	R^2
2004/05 Season										
1	90.3	14.7	-29.70	0.49	0.62	0.975	0.42	2.83	0.039	0.974
2	94.7	16.6	-26.58	0.46	0.91	0.938	0.63	2.74	0.050	0.955
3	88.4	14.1	-24.82	0.44	0.72	0.964	0.82	2.68	0.046	0.968
4	84.7	12.0	-22.22	0.40	0.61	0.942	0.77	2.69	0.046	0.942
5	97.2	17.8	-29.16	0.48	0.85	0.955	0.54	2.77	0.044	0.967
6	88.7	13.7	-28.47	0.48	0.65	0.968	0.31	2.90	0.045	0.965
7	90.5	15.0	-28.03	0.48	0.96	0.949	0.58	2.76	0.059	0.951
8	82.4	10.7	-24.08	0.42	0.62	0.937	0.24	2.94	0.055	0.923
9	81.7	10.4	-18.88	0.36	0.47	0.952	1.10	2.60	0.045	0.940
10	89.1	13.9	-26.35	0.45	0.72	0.964	0.39	2.84	0.054	0.959
11	85.2	12.1	-28.27	0.47	0.74	0.910	0.13	3.08	0.054	0.912
12	88.9	13.8	-25.73	0.44	0.89	0.960	0.20	2.99	0.087	0.935
13	93.0	16.0	-27.80	0.47	0.74	0.972	0.23	2.97	0.045	0.979
14	85.4	12.1	-24.49	0.43	0.51	0.968	0.38	2.85	0.042	0.961
15	86.6	12.7	-28.22	0.47	0.68	0.968	0.18	3.01	0.060	0.950
16	87.2	13.0	-23.91	0.42	0.77	0.921	0.73	2.70	0.060	0.907
17	99.9	19.1	-23.36	0.43	1.22	0.749	2.69	2.43	0.067	0.774
18	96.6	18.0	-30.56	0.50	0.57	0.974	0.38	2.85	0.029	0.982
19	95.3	16.7	-30.48	0.50	0.89	0.964	0.29	2.91	0.045	0.976
20	96.1	17.0	-28.56	0.47	0.66	0.962	0.33	2.88	0.038	0.970
21	91.5	15.6	-30.19	0.50	0.70	0.978	0.24	2.96	0.038	0.984
22	97.6	18.2	-30.07	0.49	0.94	0.957	0.50	2.79	0.049	0.966
23	93.9	15.8	-29.91	0.49	0.77	0.974	0.30	2.90	0.056	0.965
24	97.1	17.2	-30.60	0.49	0.90	0.958	0.22	2.96	0.054	0.963
25	95.6	16.8	-33.80	0.53	0.73	0.981	0.11	3.11	0.042	0.983
26	100.1	18.2	-29.79	0.48	0.84	0.975	0.58	2.74	0.054	0.968
27	98.4	18.4	-33.33	0.53	1.01	0.971	0.64	2.73	0.043	0.980
28	85.1	12.7	-21.86	0.41	0.83	0.949	0.87	2.67	0.065	0.945
29	87.2	13.4	-21.37	0.40	0.71	0.963	1.32	2.58	0.050	0.965
30	89.0	13.7	-25.56	0.44	0.51	0.983	0.33	2.88	0.037	0.983
31	90.1	14.1	-24.06	0.42	0.66	0.966	0.71	2.71	0.046	0.967
32	94.4	16.5	-23.16	0.42	0.88	0.944	1.59	2.54	0.054	0.952
33	93.1	15.7	-29.21	0.48	0.86	0.947	0.42	2.83	0.049	0.957
34	101.8	20.8	-38.02	0.58	1.26	0.947	0.21	2.98	0.052	0.966
35	95.2	17.2	-25.19	0.45	0.84	0.940	0.68	2.73	0.046	0.960
36	100.1	18.7	-24.86	0.44	0.66	0.928	1.59	2.53	0.035	0.944

NOTE: Average weights presented here are determined from only those SBT sampled which had length measurements and thus could be included in the regression analyses.

Table 8: Tow cage regression estimates for length-weight relationship for 2004/05

As can be seen from the uniformly high R^2 values, both models fit the data within tow-cages quite well. This indicates that a significant increase in precision can be gained by appropriately utilizing the length-to-weight relationship. However, there is significant variation in the estimated parameters of the relationships from cage to cage. This indicates that an overall model is not likely to provide equivalent increases in accuracy. Hence, any estimate of total catch-weight is best constructed on the basis of tow-cage specific information. Consequently the live SBT sampling from tow-cages must be continued. Furthermore, the linear model is simpler than the power relationship and has a nearly equivalent closeness of fit to the observations. Indeed, for 7 out of the 36 tow-cages from the 2003/04 season, the linear model has a higher R^2 value than the power regression. In the 2004/05 season, 12 out of the 36 tow-cages had linear model fits with higher R^2 values than the corresponding power regression. This suggests that use of the linear regression model is preferable on simplicity grounds to the power regression (though, differences in estimates derived from the two methods will be minimal).

4.3 Estimating total-catch weight

To appropriately incorporate the length-to-weight relationship information into a more precise estimate of total catch weight, we employ regression estimators of population totals. In particular, if we employ the linear regression relationship between SBT length and weight, then the estimated total catch weight is:

$$\textit{Estimated Total Catch-Weight} = \sum_{i=1}^{C} N_i \{\bar{w}_i + \hat{\beta}_i(\bar{L}_i - \bar{l}_i)\} \qquad (4.3.1)$$

where C is the total number of tow-cages for the season, $\bar{w}_i$ is the average weight of a sample of fish from the i^{th} tow-cage, $\bar{l}_i$ is the average length of the same sample of fish, N_i is the total number of SBT in the i^{th} tow-cage (including mortalities), $\bar{L}_i$ is the average length of all SBT in the tow-cage (or at least an accurate and highly precise estimate of this average) and $\hat{\beta}_i$ is the estimated slope of the linear regression relationship between SBT length and SBT weight in the i^{th} tow-cage. It is important to note that the weight average and length average are based on the same sample, so any sampled SBT for which a length is unavailable should be excluded from the calculation of the average weight in the calculation of the estimated total catch-weight. Subsequently we will refer to this method as the stereo-linear method. Note that the estimate of the weight for transfer j in tow cage i is $\bar{w}_i + \hat{\beta}_i(\bar{L}_{ij} - \bar{l}_i)$, where $\bar{L}_{ij}$ is the average length measured by stereo video for transfer j in tow cage i.

Alternatively, if the power regression relationship between SBT length and weight is used, then the estimated total catch-weight is:

$$Estimated\ Total\ Catch\text{-}Weight = \sum_{i=1}^{C} \alpha_i \sum_{j=1}^{N_i} L_{i,j}^{\hat{\beta}_i}$$

where again C is the total number of tow-cages for the season, N_i is the total number of SBT in the i^{th} tow-cage (including mortalities), $\hat{\alpha}_i$ and $\hat{\beta}_i$ are the estimated parameters of the power regression relationship between SBT length and SBT weight in the i^{th} tow-cage and $L_{i,j}$ is the length of the j^{th} SBT in the i^{th} tow-cage. Note that the estimate based on the power regression relationship requires the lengths of all SBT in each tow-cage. However, an alternate form of the estimate could be constructed based on an accurate and highly precise estimate of the distribution of lengths within a tow-cage. The linear regression approach requires only the average length within a tow-cage.

In order to investigate the likely impact of the stereo-linear method on the estimates of catch weight, the method is applied to the data from the 2003/04 and 2004/05 seasons. However the method requires the average length of fish in the tow cages as determined by stereo video measurement. These are not available for the 2004/05 season and for 2003/04 we have argued previously that the measurements which are in hand from a subset of the transfers from five tow cages are not reliable estimates of the complete cage means. For illustrative purposes, in Table 9a below, it has been assumed that the average length of all SBT in a tow-cage is 1% larger than the average length of the SBT in the 40-fish sample. This is only an assumption made for the purposes of investigating the behavior of the stereo-linear method. Table 9a presents the estimated total catch-weight in each of the 36 tow-cages from the 2003/04 and 2004/05 seasons calculated by the stereo-linear method, assuming that the average length of all SBT in a tow-cage is 1% larger than the average length of the SBT in the 40-fish sample. For comparison, the reported total catch-weight based on the existing 40-fish sample methodology is also provided, along with the associated percentage increase in estimated total catch-weight associated with the linear regression estimate. Table 9b and 9c report the same quantities under the assumption that the average lengths in the tow cages are 3% and 5% larger than the average length of SBT in the 40-fish sample:

Cage Ref	2003/04 Season			2004/05 Season		
	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase
1	106.24	125.11	-15.08%	118.69	128.51	-7.64%
2	123.73	123.98	-0.20%	140.92	145.31	-3.02%
3	136.15	138.22	-1.50%	198.10	195.51	1.32%
4	125.47	123.44	1.64%	136.64	151.09	-9.56%
5	153.63	149.34	2.87%	165.61	161.16	2.76%
6	112.72	121.16	-6.97%	145.64	149.36	-2.49%
7	108.03	106.84	1.11%	115.41	112.21	2.85%
8	129.13	128.99	0.11%	201.56	196.45	2.60%
9	105.37	103.99	1.33%	136.43	153.66	-11.21%
10	222.35	216.16	2.86%	145.51	161.07	-9.66%
11	217.96	214.75	1.49%	109.23	111.59	-2.11%
12	151.18	149.06	1.42%	107.69	105.70	1.88%
13	203.07	199.91	1.58%	152.33	148.75	2.41%
14	156.80	164.69	-4.79%	131.42	127.67	2.94%
15	159.81	157.55	1.43%	139.35	136.18	2.33%
16	103.43	100.68	2.73%	159.49	155.11	2.82%
17	122.31	119.16	2.64%	180.35	175.65	2.68%
18	135.55	131.96	2.72%	105.94	103.01	2.84%
19	148.30	148.37	-0.05%	135.00	137.72	-1.98%
20	80.85	78.76	2.65%	135.90	140.92	-3.56%
21	142.11	138.37	2.70%	176.27	176.69	-0.24%
22	78.27	76.17	2.76%	123.05	120.37	2.23%
23	80.54	78.29	2.87%	140.97	137.26	2.70%
24	87.05	84.75	2.71%	171.16	172.11	-0.55%
25	49.05	47.94	2.32%	91.82	90.15	1.85%
26	85.03	82.94	2.52%	158.73	154.65	2.64%
27	122.34	120.04	1.92%	104.12	101.79	2.29%
28	187.67	181.64	3.32%	165.15	160.55	2.87%
29	207.09	201.45	2.80%	210.46	205.02	2.65%
30	157.78	153.20	2.99%	118.31	117.29	0.87%
31	189.40	184.77	2.51%	156.31	152.01	2.83%
32	130.21	126.69	2.78%	227.40	221.25	2.78%
33	139.32	136.59	2.00%	92.86	90.15	3.01%
34	208.09	202.54	2.74%	168.08	167.14	0.56%
35	123.01	119.69	2.77%	113.67	127.66	-10.96%
36	126.35	122.93	2.78%	128.22	124.46	3.02%
Total	4915.39	4860.12	1.14%	5207.79	5215.18	-0.14%

Table 9a: Stereo-linear catch estimates for tow cages with a 1% assumption

Cage Ref	2003/04 Season			2004/05 Season		
	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase
1	111.45	125.11	-10.92%	124.98	128.51	-2.75%
2	129.08	123.98	4.11%	148.03	145.31	1.87%
3	143.16	138.22	3.57%	207.63	195.51	6.20%
4	131.42	123.44	6.46%	144.27	151.09	-4.51%
5	162.23	149.34	8.63%	174.52	161.16	8.29%
6	118.82	121.16	-1.93%	153.41	149.36	2.71%
7	113.46	106.84	6.20%	121.82	112.21	8.56%
8	135.69	128.99	5.19%	211.78	196.45	7.80%
9	111.34	103.99	7.07%	145.03	153.66	-5.62%
10	234.72	216.16	8.59%	153.49	161.07	-4.71%
11	229.05	214.75	6.66%	115.30	111.59	3.32%
12	158.65	149.06	6.43%	113.37	105.70	7.26%
13	213.85	199.91	6.97%	159.49	148.75	7.22%
14	164.93	164.69	0.15%	138.91	127.67	8.80%
15	168.10	157.55	6.70%	145.70	136.18	6.99%
16	108.92	100.68	8.18%	168.25	155.11	8.47%
17	128.59	119.16	7.91%	189.75	175.65	8.03%
18	142.72	131.96	8.15%	111.79	103.01	8.52%
19	156.48	148.37	5.47%	142.94	137.72	3.79%
20	85.03	78.76	7.96%	144.37	140.92	2.45%
21	149.58	138.37	8.10%	186.21	176.69	5.39%
22	82.47	76.17	8.27%	128.40	120.37	6.67%
23	85.03	78.29	8.61%	148.39	137.26	8.11%
24	91.65	84.75	8.14%	182.24	172.11	5.89%
25	51.26	47.94	6.93%	96.93	90.15	7.52%
26	89.19	82.94	7.54%	166.88	154.65	7.91%
27	128.87	120.04	7.36%	110.32	101.79	8.38%
28	197.76	181.64	8.87%	174.36	160.55	8.60%
29	218.38	201.45	8.40%	221.35	205.02	7.97%
30	166.95	153.20	8.98%	124.95	117.29	6.53%
31	198.65	184.77	7.51%	164.90	152.01	8.48%
32	137.25	126.69	8.34%	239.71	221.25	8.34%
33	147.43	136.59	7.94%	98.29	90.15	9.03%
34	219.18	202.54	8.22%	176.71	167.14	5.73%
35	129.65	119.69	8.32%	119.88	127.66	-6.09%
36	133.20	122.93	8.35%	135.75	124.46	9.07%
Total	5174.19	4860.12	6.46%	5490.12	5215.18	5.27%

Table 9b: Stereo-linear catch estimates for tow cages with a 3% assumption

Cage Ref	2003/04 Season			2004/05 Season		
	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase	Regression Catch-Weight Estimate (tonnes)	40-Fish Sample Catch-Weight Estimate (tonnes)	Percentage Increase
1	116.66	125.11	-6.75%	131.27	128.51	2.15%
2	134.44	123.98	8.44%	155.14	145.31	6.76%
3	150.16	138.22	8.64%	217.15	195.51	11.07%
4	137.36	123.44	11.28%	151.89	151.09	0.53%
5	170.82	149.34	14.38%	183.44	161.16	13.82%
6	124.91	121.16	3.10%	161.19	149.36	7.92%
7	118.89	106.84	11.28%	128.23	112.21	14.28%
8	142.25	128.99	10.28%	222.01	196.45	13.01%
9	117.31	103.99	12.81%	153.63	153.66	-0.02%
10	247.10	216.16	14.31%	161.48	161.07	0.25%
11	240.14	214.75	11.82%	121.38	111.59	8.77%
12	166.13	149.06	11.45%	119.05	105.70	12.63%
13	224.63	199.91	12.37%	166.65	148.75	12.03%
14	173.06	164.69	5.08%	146.41	127.67	14.68%
15	176.40	157.55	11.96%	152.05	136.18	11.65%
16	114.42	100.68	13.65%	177.01	155.11	14.12%
17	134.88	119.16	13.19%	199.14	175.65	13.37%
18	149.89	131.96	13.59%	117.65	103.01	14.21%
19	164.65	148.37	10.97%	150.88	137.72	9.56%
20	89.22	78.76	13.28%	152.85	140.92	8.47%
21	157.06	138.37	13.51%	196.14	176.69	11.01%
22	86.66	76.17	13.77%	133.75	120.37	11.12%
23	89.51	78.29	14.33%	155.81	137.26	13.51%
24	96.25	84.75	13.57%	193.33	172.11	12.33%
25	53.47	47.94	11.54%	102.04	90.15	13.19%
26	93.36	82.94	12.56%	175.03	154.65	13.18%
27	135.40	120.04	12.80%	116.53	101.79	14.48%
28	207.86	181.64	14.44%	183.57	160.55	14.34%
29	229.67	201.45	14.01%	232.24	205.02	13.28%
30	176.11	153.20	14.95%	131.59	117.29	12.19%
31	207.91	184.77	12.52%	173.50	152.01	14.14%
32	144.28	126.69	13.88%	252.02	221.25	13.91%
33	155.53	136.59	13.87%	103.71	90.15	15.04%
34	230.28	202.54	13.70%	185.34	167.14	10.89%
35	136.29	119.69	13.87%	126.09	127.66	-1.23%
36	140.05	122.93	13.93%	143.27	124.46	15.11%
Total	5433.01	4860.12	11.79%	5772.46	5215.18	10.69%

Table 9c: Stereo-linear catch estimates for tow cages with a 5% assumption

The choice of a percentage increase in the average length of the SBT in the 40-fish sample is designed to account for a possible decreased sampling propensity of longer SBT. The actual value is unknown and the values 1%, 3% and 5% are provided purely for indicative purposes. Of course, it is unlikely that the actual discrepancy between the average length of sampled SBT and the average length of all SBT in a tow-cage will be constant across all tow-cages. However, in a study of the stereo-video length measurement system (Harvey et al, 2005), lengths of a large number of SBT transferred from 5 different tow-cages during the 2003/04 season (tentatively identified as deriving from the tow-cages with cage reference numbers 5, 17, 21, 24 and 33) indicated that the percentage increases in the average length of all SBT in transfers monitored for a tow cage from the average length of the 40-fish sample were 4.3%, 4.2%, 6.3%, 2.8% and 5.4%, respectively, which averages 4.5%. While there are major questions as to the representative nature of the SBT length measurements taken from each of the tow-cages in this study, the general size of the percentage increases may give some credence to an overall positive increase, although its magnitude has not been established. It could be argued that the 5% used for the calculations in the above table 9c is in some sense an upper bound, since the observed average was 4.5%. Moreover, the sizes of the SBT in the 40-fish samples during the 2004/05 season are noticeably larger than those of the 2003/04 season, perhaps indicating that the percentage increase in the average length of all SBT in a tow-cage for this season is substantially less than 2003/04. If 3% is used, the overall total catch-weight estimate for 2004/05 is only 5.3% larger than the catch-weight estimate based on the 40-fish samples. If 1% is use, the overall catch-weight estimate is .14% smaller (the reduction is due to the less than 10 kilogram rule). So, it appears that, overall, even if lengths in the 40 fish sample are smaller on average than the whole cage, the current estimation procedure is providing only slight underestimates. However, on an individual cage basis the 40 fish sample based estimates are not very accurate.

4.4 Accuracy and precision of total-catch weight regression estimates

As with the 40-fish sampling scheme, the accuracy of any catch-weight estimation procedure depends on changes in length and weight characteristics being small from the time of capture to the time of transfer. However, the accuracy of the regression estimation procedure no longer depends on the differential sampling potential of SBT in the 40-fish sample (though the precision will depend on this differential sampling propensity to some degree; see below). Instead, the accuracy of the regression estimation depends on three assumptions:

1. The mortalities have a representative length distribution;

2. Either the mean length, in the case of the linear regression approach, or the entire length distribution, in the case of the power regression approach, are known exactly or is estimated with accuracy and high precision;

3. The structure of the model chosen, either linear or power regression, is an appropriate representation of the true relationship between SBT length and weight.

The first of these assumptions, while technically required to ensure an unbiased estimate of total catch-weight, is not of major concern given the relatively small number of mortalities seen. The second and third assumptions are more critical. In the case of the linear regression approach, it is sufficient to have an accurate and precise estimate of the average length of SBT in a given tow-cage. This can be achieved with a moderately sized, representative sample. Of course, if all SBT can be measured via the stereo-video system, this will provide the exact average length. However even if complete measurement of all SBT in the tow-cage proves difficult or unattainable, the accurate estimation of total catch weight is still feasible provided a representative sample of lengths is available. To this end, it should be noted that reports indicate that the order in which SBT transfer from the tow-cages to the farm cages is not necessarily random. Thus a sample consisting of all the SBT transferred during some contiguous interval of time will not necessarily provide a representative sample. Finally, the suitability of the model can readily be checked by plotting the weights versus the lengths of the SBT sampled within each tow-cage and verifying the linear or power structure on these plots.

If the linear regression structure is employed, the accuracy of the catch-weight estimate for a given tow-cage when the exact average length of all SBT in the tow-cage, $\bar{L}_i$, is known, has the form:

$$\text{Precision for Cage } i = \hat{\sigma}_i \sqrt{\frac{N_i(N_i - n_i)}{n_i} + \frac{\{N_i(\bar{L}_i - \bar{l}_i)\}^2}{(n_i - 1)s_{l,i}^2}} \qquad (4.4.1)$$

where n_i is the size of the sample of SBT taken from the i^{th} cage for determining the length to weight linear relationship, N_i is the total number of SBT in the i^{th} cage (including mortalities), $\bar{l}_i$ is the average length of the SBT in the sampled from the i^{th} cage, $s_{l,i}^2$ is the sample variance of the lengths of the sampled SBT from the i^{th} cage and $\hat{\sigma}_i^2$ is the mean-squared error from the linear regression of the weights on the lengths of the sampled SBT from the i^{th} cage. The precision for the overall catch-weight estimate is then calculated as:

$$\text{Overall Precision} = \sqrt{\sum_{i=1}^{C} (\text{Precision for Cage } i)^2} \ .$$

So, while any differential sampling propensity for SBT of various sizes no longer affects the accuracy of the catch-weight estimates, the precision is affected by two aspects of the 40-fish sample:

1. The degree to which the average length in the sample accurately approximates the overall average length of all SBT in the tow-cage; and,

2. The variation in the lengths of the sampled SBT.

Indeed, the more representative the sample, the more precise the catch-weight estimate. Since the estimates are now essentially unbiased regardless of the representative nature of the sampled SBT, the estimates will not tend to either under- or over-estimate the true catch-weight, and thus it is in the interests of all concerned to achieve as representative a sample of SBT as possible, in order to ensure as precise an estimate as possible and to minimize the chance of error in either direction.

If we assume again that the actual average SBT length in each tow-cage is a certain percentage larger than the average of the sampled SBT, then the precision for the 2003/04 and 2004/05 estimates based on the linear regression estimates of catch-weight are given in table 10 below. Note again that the review is making the 1%, 3% and 5% assumptions for illustrative purposes only and is not suggesting that it is the actual bias or indeed if a bias exists.

Cage Ref No.	2003/04 Season					2004/05 Season			
	Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight		Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight
1	74	0.81	1.50	42		55	1.06	1.66	39
2	42	0.82	1.30	18		47	1.09	1.45	25
3	44	1.08	1.56	27		41	1.57	1.49	22
4	41	1.02	1.60	26		54	1.21	1.65	38
5	40	1.13	1.45	21		40	1.38	1.55	24
6	51	0.88	1.53	30		45	1.02	1.30	20
7	40	1.18	2.14	46		40	0.98	1.58	24
8	42	0.99	1.51	24		40	1.81	1.68	28
9	42	0.86	1.60	27		87	0.90	1.21	31
10	40	2.40	2.12	45		83	0.77	0.98	19
11	41	1.51	1.36	19		46	0.61	1.03	13
12	41	1.19	1.55	25		41	0.81	1.40	20
13	41	1.54	1.49	23		40	1.33	1.63	26
14	48	1.33	1.66	33		40	0.94	1.33	18
15	41	1.07	1.31	18		40	0.87	1.17	12
16	40	0.82	1.55	24		40	1.37	1.59	26
17	40	0.94	1.51	23		40	1.16	1.20	14
18	40	0.99	1.43	21		40	1.05	1.84	33
19	43	1.27	1.68	30		49	0.85	1.16	16
20	40	0.56	1.36	19		50	1.05	1.42	26
21	40	1.50	2.07	43		44	1.41	1.49	25
22	40	0.86	2.16	47		40	1.43	2.18	39
23	40	0.51	1.25	16		40	0.74	0.98	9
24	40	0.77	1.72	30		47	1.68	1.81	35
25	40	0.69	2.77	76		41	0.82	1.65	28
26	40	0.79	1.81	33		40	1.25	1.46	21
27	41	0.94	1.51	23		41	0.79	1.41	21
28	39	1.75	1.83	33		40	1.70	1.91	37
29	40	1.60	1.52	23		40	1.77	1.57	25
30	40	1.25	1.55	24		42	0.89	1.40	21
31	40	1.31	1.36	19		40	1.54	1.83	34
32	40	1.26	1.90	36		40	1.93	1.58	25
33	41	0.97	1.37	19		40	0.65	1.29	17
34	40	1.75	1.65	27		40	1.24	1.38	20
35	40	0.87	1.38	19		35	1.06	1.74	28
36	40	1.09	1.69	29		40	0.88	1.27	16

* Includes all SBT sampled for which both weight and length measurements were available

Table 10a: Precisions of stereo-linear method with 1% assumption

Cage Ref No.	2003/04 Season					2004/05 Season			
	Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight		Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight
1	74	0.84	1.47	40		55	1.13	1.69	38
2	42	0.87	1.32	18		47	1.17	1.48	25
3	44	1.14	1.56	27		41	1.75	1.58	23
4	41	1.08	1.61	26		54	1.29	1.66	37
5	40	1.31	1.59	25		40	1.49	1.59	24
6	51	0.91	1.51	29		45	1.10	1.33	19
7	40	1.33	2.29	52		40	1.11	1.70	25
8	42	1.11	1.61	27		40	2.00	1.77	28
9	42	0.92	1.62	27		87	1.02	1.30	32
10	40	2.69	2.25	51		83	0.86	1.05	20
11	41	1.64	1.40	20		46	0.65	1.05	12
12	41	1.28	1.58	26		41	0.88	1.45	20
13	41	1.69	1.55	25		40	1.44	1.70	27
14	48	1.38	1.64	32		40	1.01	1.35	18
15	41	1.26	1.47	22		40	1.04	1.34	14
16	40	0.86	1.56	24		40	1.48	1.63	25
17	40	1.01	1.54	24		40	1.31	1.29	14
18	40	1.08	1.49	22		40	1.19	1.98	34
19	43	1.35	1.69	31		49	0.95	1.23	17
20	40	0.60	1.37	19		50	1.14	1.46	25
21	40	1.60	2.10	44		44	1.53	1.53	24
22	40	0.92	2.18	47		40	1.74	2.55	47
23	40	0.55	1.27	16		40	0.84	1.06	10
24	40	0.82	1.75	31		47	1.98	2.00	38
25	40	0.75	2.85	80		41	0.90	1.74	28
26	40	0.86	1.88	35		40	1.37	1.54	21
27	41	0.99	1.50	23		41	0.87	1.47	20
28	39	1.90	1.88	35		40	1.83	1.96	36
29	40	1.73	1.56	24		40	1.93	1.63	25
30	40	1.35	1.58	25		42	0.96	1.42	21
31	40	1.44	1.42	20		40	1.67	1.89	33
32	40	1.34	1.91	36		40	2.11	1.64	25
33	41	1.05	1.39	20		40	0.69	1.31	17
34	40	1.88	1.68	28		40	1.32	1.40	19
35	40	0.93	1.41	20		35	1.13	1.75	26
36	40	1.19	1.75	31		40	0.96	1.31	16

* Includes all SBT sampled for which both weight and length measurements were available

Table 10b: Precisions of stereo-linear method with 3% assumption

Cage Ref No.	2003/04 Season					2004/05 Season			
	Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight		Actual Sample Size*	Estimated Standard Deviation of SBT weights (kg)	95% Confidence Limit as Percentage of Catch-Weight Estimate	Sample Size Required to Obtain 95% Confidence Limit of 2% of Catch-Weight
1	74	0.89	1.49%	41		55	1.13	1.69	39
2	42	0.95	1.39%	20		47	1.17	1.48	26
3	44	1.26	1.64%	30		41	1.75	1.58	26
4	41	1.17	1.68%	29		54	1.29	1.66	37
5	40	1.62	1.85%	34		40	1.49	1.59	25
6	51	0.98	1.54%	30		45	1.10	1.33	20
7	40	1.58	2.60%	67		40	1.11	1.70	29
8	42	1.32	1.82%	35		40	2.00	1.77	31
9	42	1.02	1.71%	31		87	1.02	1.30	37
10	40	3.19	2.53%	64		83	0.86	1.05	23
11	41	1.87	1.53%	24		46	0.65	1.05	13
12	41	1.43	1.69%	29		41	0.88	1.45	21
13	41	1.95	1.70%	30		40	1.44	1.70	29
14	48	1.48	1.68%	34		40	1.01	1.35	18
15	41	1.58	1.76%	32		40	1.04	1.34	18
16	40	0.95	1.63%	27		40	1.48	1.63	27
17	40	1.14	1.65%	27		40	1.31	1.29	17
18	40	1.25	1.63%	27		40	1.19	1.98	39
19	43	1.50	1.79%	34		49	0.95	1.23	19
20	40	0.66	1.44%	21		50	1.14	1.46	27
21	40	1.79	2.23%	50		44	1.53	1.53	26
22	40	1.01	2.29%	52		40	1.74	2.55	65
23	40	0.62	1.35%	18		40	0.84	1.06	11
24	40	0.91	1.85%	34		47	1.98	2.00	47
25	40	0.84	3.08%	94		41	0.90	1.74	31
26	40	0.98	2.06%	42		40	1.37	1.54	24
27	41	1.08	1.56%	25		41	0.87	1.47	22
28	39	2.16	2.04%	41		40	1.83	1.96	38
29	40	1.97	1.68%	28		40	1.93	1.63	27
30	40	1.53	1.70%	29		42	0.96	1.42	21
31	40	1.66	1.56%	24		40	1.67	1.89	36
32	40	1.48	2.01%	40		40	2.11	1.64	27
33	41	1.19	1.50%	23		40	0.69	1.31	17
34	40	2.11	1.79%	32		40	1.32	1.40	19
35	40	1.06	1.52%	23		35	1.13	1.75	27
36	40	1.36	1.91%	36		40	0.96	1.31	17

* Includes all SBT sampled for which both weight and length measurements were available

Table 10c: Precisions of stereo-linear method with 5% assumption

So, for example under the 5% assumption, the 40-fish sample size is sufficient to produce individual cage catch-weight estimates using the linear regression procedure that are within 2% of the true value at the 95% confidence level for 28 of the 36 tow-cages in the 2003/04 season, and for 34 of the 36 tow-cages in the 2004/05 season. Alternatively, the sample size necessary to achieve estimates within 1% of the true value at the 95% confidence level (i.e., twice as precise) is readily determined by multiplying the given sample size value by a factor of four.

The overall accuracy of the linear regression estimate of total catch-weight is given in table 11.

Confidence Level	2003/04 Season			2004/05 Season	
	Confidence Limit (in tonnes)	Percentage of Estimate		Confidence Limit (in tonnes)	Percentage of Estimate
98%	16.5	0.34%		15.9	0.31%
95%	13.9	0.28%		13.4	0.26%
90%	11.7	0.24%		11.2	0.22%
85%	10.2	0.21%		9.8	0.19%

Table 11a: Accuracy of stereo-linear method with 1% assumption

Confidence Level	2003/04 Season			2004/05 Season	
	Confidence Limit (in tonnes)	Percentage of Estimate		Confidence Limit (in tonnes)	Percentage of Estimate
98%	17.9	0.35%		16.9	0.31%
95%	15.1	0.29%		14.2	0.26%
90%	12.7	0.24%		11.9	0.22%
85%	11.1	0.21%		10.4	0.19%

Table 11b: Accuracy of stereo-linear method with 3% assumption

Confidence Level	2003/04 Season			2004/05 Season	
	Confidence Limit (in tonnes)	Percentage of Estimate		Confidence Limit (in tonnes)	Percentage of Estimate
98%	20.5	0.37%		18.6	0.36%
95%	17.2	0.33%		15.7	0.27%
90%	14.4	0.27%		13.1	0.23%
85%	12.6	0.23%		11.5	0.20%

Table 11c: Accuracy of stereo-linear method with 5% assumption

Further, in order to achieve confidence limits of either 0.5% or 0.25% of the total catch-weight estimates, the required sample size of SBT per tow cage are given in table 12.

Confidence Level	2003/04 Season			2004/05 Season	
	Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%		Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%
98%	75	19		65	16
95%	53	13		46	11
90%	37	9		32	8
85%	29	7		25	6

Table 12a: Sample sizes for accuracy of stereo-linear method with 1% assumption

Confidence Level	2003/04 Season			2004/05 Season	
	Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%		Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%
98%	79	20		65	13
95%	56	14		46	11
90%	39	10		32	8
85%	30	8		25	6

Table 12b: Sample sizes for accuracy of stereo-linear method with 3% assumption

Confidence Level	2003/04 Season			2004/05 Season	
	Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%		Sample Size for Confidence Limit of 0.25%	Sample Size for Confidence Limit of 0.5%
98%	93	23		71	18
95%	66	16		51	13
90%	46	12		36	9
85%	35	9		27	7

Table 12c: Sample sizes for accuracy of stereo-linear method with 5% assumption

If we employ the power regression estimation methodology, the direct calculation of catch-weight estimates and standard deviations requires the entire distribution (or at least an accurate and highly precise estimate of the distribution) of the SBT lengths in each tow-cage. Very limited information exists regarding these distributions. Thus, since entire distributional structures are quite complex, any supposition regarding these distributions may lead to unreliable calculations. Nevertheless, the close similarity between the linear regression and power regression model fits within each tow-cage indicates that the catch-weight estimates and their associated precisions are likely to be quite similar to those derived by the linear regression approach. Finally it should be noted that these sample size recommendations do not take into account any errors in the length or weight measurements. A more extensive analysis could adjust for those factors if more information was available.

4.4 Issues and discussion

The calculations of precision and sample size for the linear regression estimate of catch-weight outlined in the previous section assumed that the average length of all SBT in each tow-cage was known exactly. If, instead, we only have an estimate of the average SBT length, there will be an additional component to the precision of the estimate. The average SBT length may be an estimate rather than an exact value for a variety of reasons including:

1. Intrinsic error in the measurements of SBT lengths. For example the stereo-video system has a small imprecision associated with its length measurements;

2. Only a subset of the SBT from a given tow-cages are able to be measured.

The catch-weight estimates from tow-cages will remain unbiased as long as the estimate of the average length of SBT within the tow-cage is also unbiased. It should be noted that the individual stereo-video measurements were shown in section 3 to be essentially unbiased. In addition, in a trial of the stereo-video system on actual SBT transfers from tow-cages to farm cages during the 2003/04 season, there appeared to be a relationship between SBT length and the time during the transfer (i.e., SBT of varying sizes tended to swim through the transfer gates at different times). Thus, if only a subset of SBT lengths are measured, and this subset is not randomly chosen throughout the duration of the transfer, the average length calculated from this subset could be a biased estimate.

It is clear that any sampling scheme for length cannot be time based. For example, consider the hypothetical situation where all the large tuna swim through the transfer gate in the first 10 minutes of a 60 minute transfer with the remainder swimming through in a random order and equally spaced over the whole hour. Any time based sampling scheme would grossly underestimate the number of large fish under that hypothetical scenario. Alternatively, sampling schemes based on the position number of fish in the transfer may be difficult to implement and costly, since finding a particular fish in the video record might be quite time consuming and difficult to pinpoint unambiguously. Consequently, the review is of the opinion, that until more data is available, the average length should be obtained as the average length of as many fish as can be measured.

If the estimate of the average SBT length in the i^{th} tow-cage is unbiased, then the standard deviation of the catch-weight estimate based on the linear regression estimate is increased by an amount:

$$SD(\bar{L}_i)N_i\sqrt{\hat{\beta}_i^2+\frac{\hat{\sigma}_i^2}{(n_i-1)s_{l,i}^2}}$$

where $SD(\bar{L}_i)$ is the standard deviation of the estimate of the average SBT length within the i^{th} tow-cage. Of course, if this value is negligible, then the precision estimates calculated above will be essentially unchanged. However, if the precision of the average SBT length estimate is not sufficiently high, then this additional term must be accounted for, both in terms of actual precision calculations as well as sample size determinations.

The same issues arise in the power regression estimation approach. In that case, the entire distribution of the SBT lengths within a tow-cage is required to determine the catch-weight estimate and its precision. It is useful to know how large a sample of SBT lengths is necessary to ensure a sufficient level of precision in the estimate of the entire distribution of SBT lengths. One approach to assessing the precision of a distributional estimate is the one-sample Kolmogorov-Smirnov test. However, as the sample in this case is drawn from the finite population within the tow-cage, a finite population correction factor should be employed. The appropriate test statistic for the i^{th} tow-cage has the form:

$$KS_i = D_{\max,i}\sqrt{\frac{n_i(N_i - n_i)}{N_i - 1}}$$

where $D_{\max,i}$ is the largest deviation between the distribution of the sampled SBT lengths and the actual distribution of all the SBT lengths in the i^{th} tow-cage. The quantiles, Q_p, of the distribution of the statistic KS_i for various percentage points, p, are given in table 13.

Percentage Point, p	Associated Quantile, Q_p
0.85	1.138
0.9	1.224
0.95	1.358
0.975	1.480
0.98	1.517
0.99	1.628
0.995	1.731

Table 13: Quantiles of the Kolmogorov Smirnov Statistic

Thus, to ensure a confidence level, $1\text{-}\alpha$, that the maximum deviation between the length distribution of the sampled SBT differs from the overall distribution of the N total SBT lengths in an entire tow-cage by no more than a specified amount, d, we need a sample size of:

$$n = \frac{NQ_{1-\alpha}^2}{(N-1)d^2 + Q_{1-\alpha}^2}$$

In particular, figure 9 shows the sample size necessary to ensure a maximum difference of 2% between the length distribution of sampled SBT and the overall distribution of SBT in a tow-cage with various total numbers of SBT at three different levels of confidence: 90%, 95% and 99%. Finally, we reiterate that these sample size guidelines are only relevant if the samples are truly random samples from the whole tow cage.

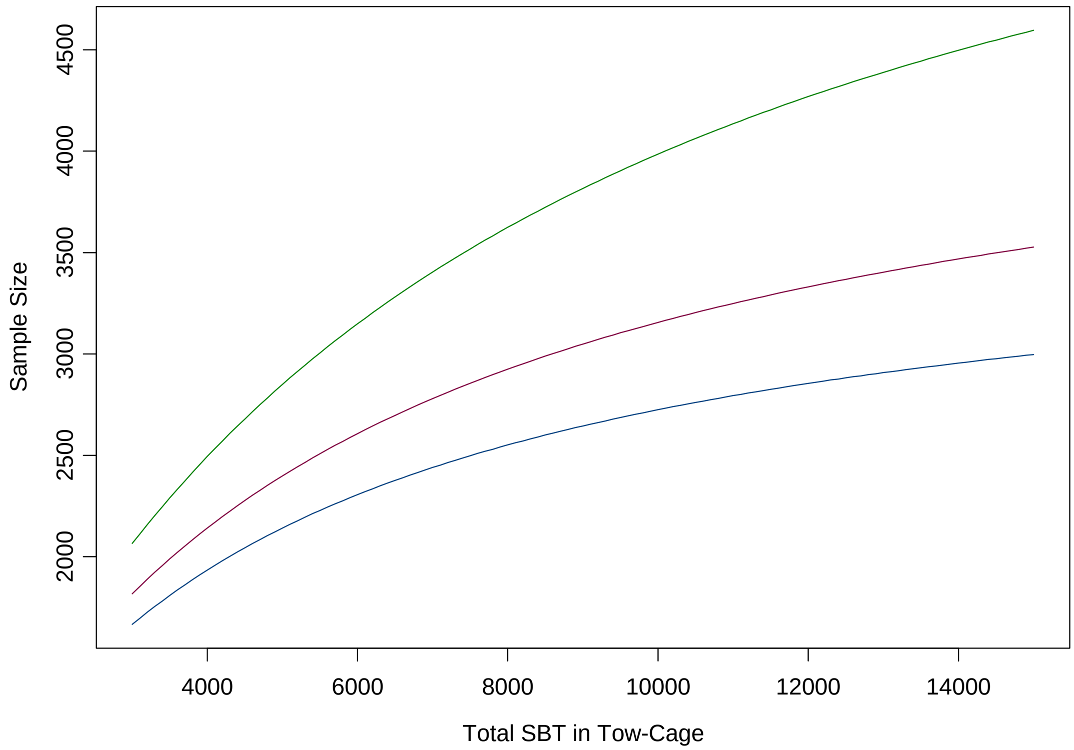

Figure 9: Sample Size Necessary to Ensure Maximum 2% Difference in Distribution Estimate; Blue = 90% Confidence; Red = 95% Confidence; Green = 99% Confidence

5. Catch estimation methods and cost benefit analysis

5.1 The options

The previous sections have described in detail the current method for estimating the catch as well as the trials conducted to assess the stereo video system for measuring length. Section 4 examined the use of stereo video data in conjunction with length weight regression to estimate the catch. In the opinion of the review, there are only two viable methods of estimation of the catch:

- The existing method, which combines the fish sample with an underwater video count;
- The stereo-linear method which uses a fish sample with an underwater stereo video measurement of essentially all the fish in the tow cage and a video count of the fish as well.

Other additional sources of information have been suggested to the review. Otoliths are collected from mortalities and can provide information on the age distribution of the mortalities. However, no information is available on whether the mortalities can be regarded as a representative sample of fish in the tow cage, so this is not thought to be useful for catch estimation. Tag return data was also suggested but not considered to be directly relevant to review.

Another available set of information is the harvest weight of the fish. It has been suggested that these weights, in combination with observed grow-out rates for fish could be used to impute a catch weight for the fish. In the opinion of the review, there is considerable uncertainty inherent in this approach. It would appear to require several experimental cages which would need to be very closely matched to conditions in the grow-out cages and the design issues would be formidable. It is not recommended.

5.2 Some management issues

In considering the cost benefit of any approach a number of issues have arisen in discussion with participants in the review. These issues are as follows:

1. The need for zero bias in estimates of catch;

2. The need for precise estimates for total catch;

3. The need for precise estimates for each tow cage as well as total catch.

The approach that the manager takes to these issues is a policy question and is outside the terms of this review. Given this, we comment briefly on the statistical issues involved in each point but provide no recommendation.

Bias in catch estimates does not necessarily preclude their use as a component of the quota setting and verification process. If bias is a consistent factor over years, then it is still possible to use it to institute relative cuts to the overall quota. As an example, if the quota was 100 tonnes, but there was a bias of 2% in the measurement process, the actual catch would be 102 tonnes. If the quota was reduced by 50 percent to 50 tonnes and the same measurement process used the new actual catch would be 51 tonnes. Thus the nominal quota has been reduced by the same factor as the actual catch. Provided that the bias does not change over time these arguments hold.

The fact that there is statistical uncertainty in the estimate of total catch does not necessarily preclude its use as a management device. The use of a statistical estimate means that each year the estimate of catch is equal to the quota, but the actual catch is different. For example the quota may be 100 tonnes, but over several seasons the actual catch could be 97, 103, 99, 101, 100 102, 97. Thus in some years the quota holder gets more than the nominal quota and in some years less. Whether this variation has any practical impact on the management of the fishery is a question for the manager.

The final issue is the difference between tow cage level estimates and the overall total. Sections 2 and 4 have demonstrated that the tow cage estimates may have significantly higher uncertainty than the overall estimate. What this means is that the manager may have good confidence in the overall catch but will be more uncertain about the individual quotas. The practical implications of this system is that in a given year some quota holders receive more than their quota and some less, but on average, over the seasons, each quota holder will receive their expected quota (ignoring possible biases). Whether additional expenditure should occur to increase the precision of the cage level estimates will depend on the responsibilities of the manager to track the quota as well as the commercial decisions of the quota holders.

5.3 The 40 fish sample with video count

The current method has been effectively used for many seasons and has been judged to be a reliable and cost effective method of estimating the catch. However some parties consider that the method may give a biased underestimate of the catch, principally because they believe that larger fish are less likely to take the hook during the sampling procedure. Data to shed light on this issue has been very difficult to acquire. One strategy would be to run the forty fish sample and then harvest the cage and weigh, but this is obviously not commercially feasible. The advent of the stereo video technique for measuring the lengths of fish provides a new technique which can be utilized to provide some useful information on the question. A subset of transfers from five tow cages was measured by stereo video in the 2003/04 season. Subsequently the Bureau of Rural Sciences analyzed the transfer data, and concluded that the existing method gave a negatively biased estimate of the catch. For reasons described in section 3.4.5, in the opinion of the review, the Bureau of Rural Sciences results do not have a sound statistical basis and any bias of the existing method has not been demonstrated statistically. Nevertheless there are some aspects of the data, such as the absence of large fish in the 40 fish samples in 2003/04, which indicate that during 2003/04 large fish were less likely to take the hook. However when we look across seasons, the position is not so clear. As shown in table 6, during the 2004/05 season, which overall had many more small fish, quite a few large fish were hooked and measured during the forty fish sampling. So any bias in 2004/05 is likely to have been considerably smaller. If lengths could be measured for virtually all fish in the transfers, then the issue of bias in the existing procedure could be resolved once and for all. However at this point such data does not exist and the matter is still unresolved. In considering whether to modify the existing method it is important to consider when changes will impact bias or precision or both.

If the current method is to be used in the future, then some changes may be contemplated. The first change that has been contemplated is increasing the sample size. This change will increase the precision of the estimate but will do nothing to correct any systematic biases if they exist. Sample size requirements for a given level of precision, both at the cage and catch level are presented in tables 2, 3 and 4. If high precision is required at the cage level, then much larger sample sizes are required. In both the two seasons studied, 40 fish samples were sufficient to ensure that the 85% confidence limits were within 1% of the overall catch, assuming that there is no systematic bias.

At the current time, while the weighing and measuring is done by the AFMA contractor, other tasks in the sampling procedures, notably the fishing with the hand-line and the diving, are performed by tuna company staff. One possibility, to eliminate variability and perhaps have skilled individuals who are able to catch large fish, is to make those roles the responsibility of the AFMA contractors as well. Also the fishing gear could be standardized and provided by the AFMA contractor. The review sought information from the AFMA contractor about these options. The Tuna Boat Owners Association of South Australia (TBOASA) also provided opinion on the likely cost. AFMA was asked for their opinion on the costs. Standardizing the fishing gear would cost a very small amount and should be done.

The review was advised by AFMA that the present contract for the forty fish sample and video count costs about $360,000. Protech provided estimates of the cost of various modifications and enhancements to the present regime. Protech attributed about $42,000 of the present contract to the forty fish samples. They estimated that the cost of doubling to an eighty fish sample would be $300 per tow cage or of the order of $10,000 per season. They estimated that implementing AFMA catchers would require six extra staff at $350 per day for a total cost of $72,000 per season. They do not suggest that this would change with the size of the sample.

The TBOASA also provided estimates of the cost of modifying the existing regime. Their estimate of the additional cost to move to an “80 fish” sample is $91,000. Note that the 87 fish referred to in the TBOASA submission is the number of fish they assume is required on average to get 80 fish over 10 kilograms. The difference to the Protech estimate is the portion of the existing contract attributed to the “40 fish” sample, which TBOASA puts at over $90,000, and the marginal cost of adding extra fish to the sample. They also suggest that the extra mortality caused by handling extra fish should be included. The TBOASA estimate of the cost of moving to AFMA catchers is also higher.

They suggest that the Protech team at the catch would need to be increased to six people from two. They estimate that the additional costs would be

Sample Size	Industry hooks	AFMA hooks
“60 fish”	61	125
“80 fish”	111	238

Table 14: TBOASA estimates of extra costs for modified sampling regime

Finally, the TBOASA suggests that the modifications would involve extra exposure to accidental loss which the industry has estimated at $650,000.

It is very difficult to reconcile the very different estimates from the two groups. For example moving to an eighty fish sample has estimated costs of about $72,000 from Protech and $238,000 from the TBOASA. The review is not in a position to discriminate between these two bounds and sought advice from AFMA. The review is only able to use these two figures as plausible bounds for the likely cost.

With regard to the likely effectiveness of these measures, the issue of bias is the overriding concern. If one is prepared to accept that the bias of the existing method has not been resolved one way or the other, then the existing method based on a forty fish sample is doing reasonably well and can perhaps be made more precise by increasing the size of the sample. On the other hand if we are worried about bias, then the difficulty with the modifications discussed here is that it is not clear if they will fix the bias issue. Increasing the sample size will not correct the bias. Using AFMA catchers may remove any bias attributable to industry catchers, if any such bias exists. But it will do nothing about any differential propensity of fish to be hooked according to size.

Consequently the recommendations if the present method is continued are that

- Sample sizes to attain a desired level of precision subject to allowable costs should be selected from tables 2, 3 and 4. It is noted that the present forty fish sample appears to strike a reasonable balance between precision and the practical constraints and risks of sampling at sea;

- The fishing gear should be standardized and provided by the AFMA contractor;

- In light of the considerable cost of using AFMA catchers and the uncertainty of whether it will actually correct any biases which may exist, the option of using AFMA catchers is not recommended.

5.4 The stereo-linear method

The stereo video measuring technique in conjunction with a length weight sample offers a promising new method to estimate the weight of the catch. The concerns that have been raised about bias by some parties are largely resolved by the stereo-linear method. Note once again that the review does not consider that the alleged biases have been demonstrated statistically.

The two options which were considered in section 4 to map lengths to weights were linear and power regression. Power models have wider acceptance in the literature. However in the opinion of the review the advantages of linear regression are compelling in this application. Section 4 has demonstrated that, at least for the two seasons which were considered, there is a negligible difference between the fit of the linear and power regressions. The advantage of the linear method is that it only requires a simple linear regression of weight on length for the fish sample followed by average lengths measured by stereo video for all transfers. The power regression method is also feasible, but more complicated. Recall that the stereo-linear equation given in formula (4.3.1) is very simple:

$$\textit{Estimated Total Catch-Weight} = \sum_{i=1}^{C} N_i\{\bar{w}_i + \hat{\beta}_i(\bar{L}_i - \bar{l}_i)\}$$

The estimate of precision given in formula (4.4.1) is also very appealing in its simplicity and is

$$\text{Precision for Cage } i = \hat{\sigma}_i\sqrt{\frac{N_i(N_i - n_i)}{n_i} + \frac{\{N_i(\bar{L}_i - \bar{l}_i)\}^2}{(n_i - 1)s_{l,i}^2}}$$

All terms are defined in section 4. These two formula are very simple to implement in an excel spreadsheet.

The protocol for the fish sample can be modified under this method. The role of the fish sample becomes to provide estimates of the regression coefficients. Under this estimation method, it is of no consequence whether the average weight or average length of the fish sample is an unbiased estimator of the tow cage quantities. Assuming that linear regression is appropriate, the regression estimators will be unbiased estimators of the parameters. The precision of these quantities will depend on the configuration of the lengths in the fish sample. If it was possible to choose the lengths, then they could be configured to maximize the precision of the estimates. However it is not possible and the lengths will be those of the fish caught in the sample. The argument for ignoring fish less than 10 kilograms in weight no longer applies. The effect on the precision of the regression estimates will be minimal. Consequently if the stereo-linear method is adopted, then there is no reason to continue with the less than 10 kilogram rule.

There are three possible obstacles to implementing the stereo-linear method. The first is that, at this time, it has not been demonstrated that the hardware is reliable and can consistently be used without repeated hardware failure. In the most recent trials which were described in Harvey et al (2005) several transfers were missed because of hardware failure. Technology has moved on since the cameras used in these trials were constructed and there is the likelihood that new units will be more robust and reliable. Nevertheless, it is essential that the reliability of stereo video measuring be established before the stereo-linear technique is adopted. It will not be satisfactory if the units break down and some transfers are missed. In light of the clear transfer level effects which are evident in Harvey et al (2005), all transfers must be captured.

The second possible obstacle is that a count, as well as length measurement, is required. In the most recent tests the stereo video technique was only able to measure less than 90% of the fish passing through the gate. This will need to be improved to be at least over 90% but a full count is also required. If the stereo video can also be shown to be capable of doing a full count, then the existing camera could be eliminated. However that may not be possible. Advice from Euan Harvey is that the two systems can both be mounted on the transfer gate and do not interfere with each other. Also the existing video camera count has been proven over several seasons to be reliable and accurate. Consequently, it is the opinion of the review that the existing video camera count should be retained.

The third obstacle is the additional cost. On the one hand there are significant gains in accuracy for a given sample size as can be seen in tables 10, 11 and 12. Indeed, it is clear that the present forty fish regime is likely to be more than adequate. Furthermore, abolition of the less than ten kilogram strategy will limit the actual number sampled to exactly forty. The fact that the necessary sample size is much smaller for a given level of precision is a major advantage, especially in light of the high cost of additional numbers as described in the last section. On the other hand there are additional costs in the stereo linear technique. The review has relied on information provided by Euan Harvey on the capital costs and the cost of reading the digital records for the stereo video recordings. The advice is that the current cost of a single stereo video setup is approximately $35,000 and that two active units plus a backup will be required giving a total initial capital cost of $105,000. Euan estimated that the cost of reading the digital records to be $100,000 for the whole season. This figure would most likely be reduced considerably if an automated technique of reading the records was introduced. Euan Harvey did not make any allowance for costs involved in additional tasks involved such as for example the extra time involved in setting up the stereo video cameras, but let us allow an extra $10,000 for incidentals. Also suppose the stereo video cameras have a lifetime of 5 years say. This gives estimated costs of $110,000 initial capital and $110,000 annual, or alternatively an annual total cost of approximately $132,000 if the stereo video equipment is depreciated over five years, with potential savings in reduced sample sizes and automation.

Consequently the recommendations if the stereo-linear method is to be adopted are that:

- New stereo video equipment should undergo field trials for such time as necessary to demonstrate that it can successfully be used to monitor all transfers for a season and measure at least 90% of all fish in each transfer. The equipment must be practical, extremely reliable and simple to use at all times at sea;

- Sample sizes to attain a desired level of precision subject to allowable costs should be selected from tables 10, 11 and 12. It is noted that the present forty fish sample appears to strike an excellent balance between precision and the practical constraints and risks of sampling at sea. Further the precision associated with a given sample size is greater with this method than the existing procedures;

- There is no advantage to ignoring fish smaller than ten kilograms under this method, so that practice could be discontinued. However if there are other reasons why it is judged that the practice should continue, then the review has no objection;

- Consideration should be given to automating the length measurements from the digital images. If the process is automated, then consideration may be given to adding extra body measurements to the regression estimates to further increase the precision, although the impact on the precision of overall catch estimates is likely to be minor.

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