MOVEMENT, GROWTH AND AVAILABLE ABUNDANCE TO THE FISHERY OF *DISSOSTICHUS ELEGINOIDES* SMITT, 1898 AT HEARD ISLAND, DERIVED FROM TAGGING EXPERIMENTS

R. Williams✉
Australian Antarctic Division
Channel Highway, Kingston 7050
Tasmania, Australia
Email – dick_wil@antdiv.gov.au

G.N. Tuck
CSIRO Marine Laboratories
Castray Esplanade, Hobart 7000
Tasmania, Australia

A.J. Constable and T. Lamb
Australian Antarctic Division

Abstract

Stocks of Patagonian toothfish (*Dissostichus eleginoides*) in different sectors of the Southern Ocean are considered to be genetically distinct. However, in the Indian Ocean, it is largely unknown whether stocks are separate between shelves and banks separated by deep water. More particularly, the separation of stocks on the Kerguelen Plateau has not been investigated. This paper examines the assumptions of stock separation using tagged fish from the fishery around Heard Island and McDonald Islands (HIMI) in the Australian Exclusive Economic Zone (EEZ). Movement, growth and trends in fish abundance are examined using these data. The bulk of the data show that fish disperse only a very short distance, up to 15 n miles in most cases, from their point of release. This may be explained in part because of the concentration of fishing in the established grounds, which makes recaptures more likely in the same place as marking. The concentration of effort should also result in a high probability of detecting fish movements between grounds, if they occur, but so far no such movement has been detected. It appears that fish tend to be locally resident during their phase in the depth range of the fishing grounds, but they move on once they approach maturity at about 850 mm total length and become unavailable to the fishery. Four fish have been recorded as moving a long distance, and thus provide contradictory evidence. Three fish moved from ground B of HIMI to Crozet and were all within the size range normally found in the Heard Island fishing grounds, and so appear to be behaving differently from those fish that follow the normal pattern of residency in the grounds. One fish has been recorded as moving from ground A to Kerguelen and was at the upper end of the size range normally found on the grounds. These four long-range movers provide the first documented direct evidence of toothfish moving such distances and of fish moving from one fishery to another. The significance of this is discussed. Trends in abundance of fish show that the number of fish in ground B and in the population as a whole has been reduced since 1998. The implications of these results are discussed. The overall results show that mark–recapture experiments provide important information for the management of toothfish stocks and that trends in abundance derived from these experiments might be useful adjuncts to the assessment process in the future.

Résumé

Les stocks de légine australe (*Dissostichus eleginoides*) de différents secteurs de l'océan Austral sont considérés comme génétiquement distincts. Toutefois, dans l'océan Indien, il n'y a aucune évidence de la présence de stocks séparés entre les plateaux et les bancs séparés par des eaux profondes. De plus, la séparation des stocks sur le plateau de Kerguelen n'a pas été étudiée. Le présent document examine les hypothèses de séparation des stocks par le biais du marquage de poissons de la pêcherie des îles Heard et McDonald (HIMI) dans la zone économique exclusive (ZEE) de l'Australie. Ces données ont permis d'étudier les déplacements, la croissance et les tendances de l'abondance des poissons. Elles indiquent en général que, du point où ils sont relâchés, les poissons ne se dispersent que dans un court rayon d'un maximum de 15 milles nautiques dans la plupart des cas. Cela s'explique en partie par la concentration de la pêche dans les lieux établis. Les recaptures auront donc probablement lieu au même endroit que le marquage. La concentration de l'effort de pêche devrait par ailleurs augmenter les chances de détecter les déplacements des poissons d'un lieu à un autre, si toutefois ils se déplacent, ce qui reste encore à confirmer. Il semble que les poissons aient tendance à résider localement pendant la phase où ils fréquentent l'intervalle de profondeur de la pêche, mais qu'ils se déplacent lorsqu'ils approchent de la maturité à environ 850 mm de longueur totale et deviennent disponibles pour la pêcherie. Quatre poissons ont parcouru une grande distance, ce qui apporte des preuves contradictoires. Trois d'entre eux sont passés du lieu B des HIMI à Crozet, appartenant à l'intervalle de tailles normalement trouvé dans les lieux de pêche de l'île Heard. Leur comportement semble donc se différencier de celui des poissons qui normalement résident dans ces lieux. Le dernier, dont la taille figure parmi les plus élevées de l'intervalle que l'on trouve normalement sur les lieux, s'est déplacé du lieu A à Kerguelen. Ces quatre poissons migrateurs sont l'évidence directe, documentée pour la première fois, d'un déplacement de légine sur une si grande distance et d'une pêcherie à une autre. L'importance de ce point est examinée. Les tendances de l'abondance de poisson indiquent que le nombre de poissons au lieu B, ainsi que la population dans son ensemble, ont diminué depuis 1998. Les implications de ces resultats sont étudiées. Des résultats généraux, il résulte que les expériences de marquage-recapture produisent des informations importantes pour la gestion des stocks de légine et que les tendances de l'abondance dérivées de ces expériences pourraient s'avérer utiles à l'avenir dans le processus d'évaluation.

Резюме

Запасы патагонского клыкача (*Dissostichus eleginoides*) в различных секторах Южного океана считаются генетически разнородными. Однако в случае Индийского океана неизвестно, обособлены ли запасы на шельфах и банках, разделенных глубоководными участками. В частности, не исследовалось разделение запасов на плато Кергелен. В статье исследуется предположение о разобщенности запасов, используя рыбу, помеченную на промысловых участках вокруг о-вов Херд и Макдональд (HIMI) в Исключительной экономической зоне (ИЭЗ) Австралии. По этим данным изучались передвижение, рост и тенденции изменения численности рыбы. Большинство данных показывает, что рыба преимущественно перемещается на очень короткое расстояние (до 15 мор. миль) от того места, где ее выпускают. Это может быть отчасти объяснено концентрацией промысла на установившихся участках, что делает повторную поимку более вероятной в месте мечения. Концентрация усилия должна также приводить к высокой вероятности обнаружения миграции рыбы между участками (если она происходит), но пока такого перемещения замечено не было. Представляется, что на фазе обитания в диапазоне глубин промысловых участков рыба держится преимущественно локально, но перемещается и становится недоступной для промысла по достижении зрелости при общей длине примерно 850 мм. Было отмечено перемещение 4 особей на большое расстояние, что противоречит остальным данным. Три особи, размер которых был типичным для промысловых участков о-ва Херд, переместились с участка B HIMI к о-ву Крозе; такое поведение, как представляется, отличается от поведения особей с нормальной картиной локального обитания на этих участках. Одна особь, размер которой был в верхнем конце обычного для этих участков диапазона размеров, переместилась с участка A к Кергелену. Эти 4 особи, переместившиеся на большие расстояния, служат первым прямым зарегистрированным доказательством перемещения клыкача на такие расстояния, а также миграции особей с одного промыслового участка на другой. Обсуждается значимость этого факта. Тенденции в численности говорят о сокращении количества рыбы на участке B и во всей популяции с 1998 г. Обсуждается значение этих результатов. В целом результаты показывают, что эксперименты по мечению–повторной поимке дают важную информацию для управления запасами клыкача, и что полученные в результате этих экспериментов тенденции в численности могут служить полезным дополнением к процессу оценки в будущем.

Resumen

Se considera que hay una diferenciación genética de los stocks de bacalao de profundidad (*Dissostichus eleginoides*) que habitan en distintos sectores del Océano Austral. No se sabe sin embargo si en el Océano Índico hay una diferencia de este tipo entre los stocks de distintas plataformas y entre aquellos situados en bancos separados por aguas profundas. No se ha estudiado la diferenciación de stocks de la plataforma de Kerguelén. Este documento examina las hipótesis sobre la separación de stocks en base al estudio de los peces marcados en la pesquería que opera frente a las islas Heard y McDonald (IHIM) en la zona de exclusividad económica australiana (ZEE). Estos datos han sido utilizados para estudiar el desplazamiento, crecimiento y tendencias en la abundancia de peces. La mayor parte de los datos muestra que los peces sólo se trasladan trayectos muy cortos, generalmente hasta 15 millas náuticas del lugar donde fueron liberados. Esto puede ser explicado en parte por la localización de la pesca en los caladeros tradicionales, aumentando la probabilidad de que los peces sean capturados nuevamente en el mismo lugar en que fueron marcados. La concentración del esfuerzo también puede resultar en una alta probabilidad de detección del desplazamiento entre caladeros, si efectivamente esto ocurre, pero hasta ahora no se ha detectado un desplazamiento de este tipo. Aparentemente los peces tienden a mantenerse en una área localizada durante la fase cuando permanecen en el intervalo de profundidad donde se lleva a cabo la pesca, pero al alcanzar la madurez – alrededor de 850 mm de largo total – abandonan el lugar y dejan de estar disponibles para la pesquería. No obstante, las pruebas son contradictorias ya que se ha detectado el desplazamiento muy remoto de cuatro peces. Tres peces se trasladaron del caladero B de IHIM al caladero de isla Crozet, estando todos ellos dentro del intervalo de tallas que generalmente se encuentra en los caladeros de isla Heard, y por lo tanto parecen comportarse distinto a los peces que siguen la norma de permanencia en el caladero. El otro pez se trasladó del caladero A a Kerguelén; éste estaba en el límite superior del intervalo de tallas encontrado generalmente en los caladeros. Los cuatro peces que se desplazaron distancias mayores representan la primera prueba directa y documentada de desplazamientos de austromerluzas a grandes distancias y de una pesquería a otra. Se presenta una discusión sobre la importancia de estas observaciones. El examen de las tendencias en la abundancia de peces indica que la cantidad de peces en el caladero B y en la totalidad de la población ha disminuido desde 1998. Se analizan las consecuencias de estos resultados. Los resultados globales muestran que los experimentos de marcado y captura posterior brindan información importante para la ordenación de los stocks de austromerluzas y que en el futuro se pueden utilizar las tendencias en la abundancia derivadas de estos experimentos para complementar el proceso de evaluación.

Keywords: *Dissostichus eleginoides*, Heard Island, tagging, movement, growth, available biomass, CCAMLR

INTRODUCTION

Directed fisheries for Patagonian toothfish (*Dissostichus eleginoides*) have been conducted since the mid-1980s within the CCAMLR Convention Area (CCAMLR, 1994, 2002), and for longer in the Chilean Exclusive Economic Zone (EEZ). Despite considerable work on the biology of *D. eleginoides* since the start of the fisheries, little is known of the movement patterns of this species. Some genetic work has been published (Appleyard et al., 2001; Smith et al., 2001; Smith and McVeagh, 2000) which demonstrates that fish from widely separated locations (e.g. Macquarie Island, Heard Island and South Georgia) are not related, which implies little or no movement of fish between these areas. Movements on a more local scale are less well defined; Appleyard et al. (2001) found very few genetic differences between fish in different grounds within the Macquarie and Heard Island fisheries, but genetic homogeneity can be maintained by a low level of interchange of fish. Agnew et al. (1999) inferred spawning migrations of fish in the South Georgia/Shag Rocks area from observed length-frequency distributions and maturity stages, but did not observe any movements directly.

In the Indian Ocean sector, fisheries for *D. eleginoides* occur in the Australian EEZ around Heard Island and McDonald Islands (HIMI), in the French EEZs around the Kerguelen Islands and the Crozet Archipelago, and in the South African EEZ around Prince Edward and Marion Islands (Figure 1). The HIMI and Kerguelen zones are contiguous and occupy the northern part of the Kerguelen Plateau and surrounding deep water; the fishing grounds in the two areas are nowhere separated by water deeper than about 600 m. The Crozet and Prince Edward and Marion zones are isolated from each other and from the Kerguelen Plateau by extensive stretches of water deeper than 2 000 m. At present, fisheries for *D. eleginoides* in these zones are assessed and managed independently by the various governments that have jurisdiction over the respective EEZs, and thus are in effect treated as though they are separate stocks. In the case of the HIMI fishery, which is present on part of the Kerguelen Plateau, it is assumed

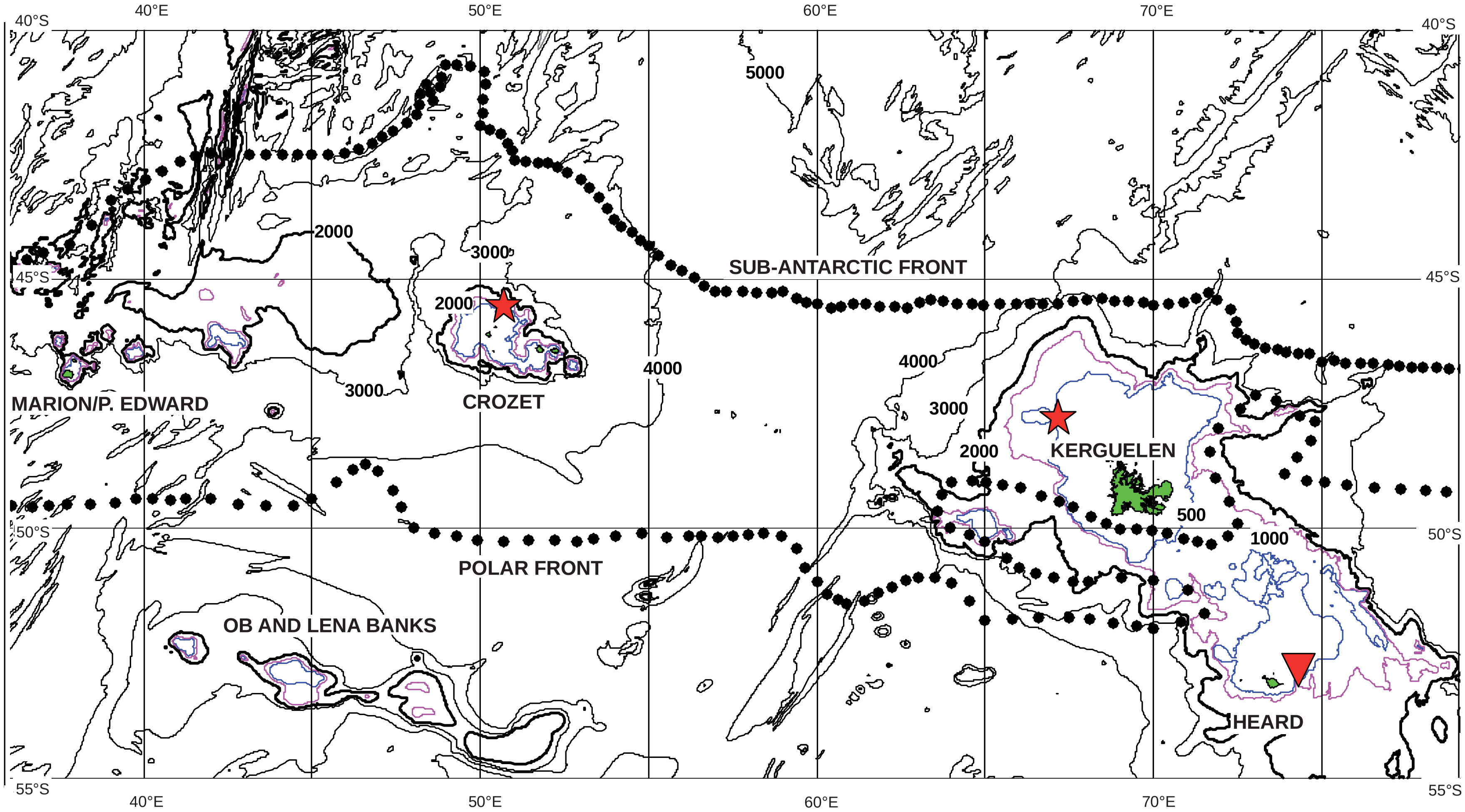

Figure 1: Map showing the relative positions of Heard, Kerguelen, Crozet and Prince Edward and Marion Islands and the movements of tagged fish between them. Oceanic front data from Park et al. (1993). Note that to protect commercial confidentiality, the exact positions of release and recapture are not shown. Triangle – release location, stars – recapture locations.

that although fish are taken from three widely separated grounds in the zone, they are all part of the same stock and there is no need to conduct separate assessments for each ground (Constable et al., 1999).

These assumptions have not been fully tested by investigating the general scale of movement of toothfish or whether there is any specific interchange of fish between grounds. Therefore a program of tagging *D. eleginoides* in the HIMI fishery was instigated, in collaboration with the trawler operators licensed to fish in the region, to investigate the extent of movement of toothfish within the Heard Island fishing area and beyond.

Besides giving information on fish movements, the tagging program provides an opportunity to estimate the growth rate of fish between release and recapture and to utilise an alternative method of stock assessment through mark–recapture techniques. Such results serve as a useful check on the von Bertalanffy growth parameters calculated from age and length data on the one hand, and on the results of assessments of abundance based on random stratified trawl surveys on the other.

MATERIALS AND METHODS

Tagging of *D. eleginoides* was commenced in the Heard Island trawl fishery (CCAMLR Statistical Division 58.5.2) in May 1998 after the fishery itself started in April 1997. The tagging program was initiated after a successful program had been running on a similar fishery at Macquarie Island since January 1996.

Fish were tagged with two separate types of tag:

- a TIRIS (Texas Instruments Remote Identification System) tag similar to those used to identify livestock (also known as 'PIT' tags) which are coded with a unique number and are interrogated by a detector system placed in the vessel's factory processing line; and
- yellow plastic T-bar tags (Hallprint, Adelaide) that carry a unique number and an inscription detailing where to report recaptures. These tags rely on being visually detected by personnel handling the fish. The tags are 50 mm in total length with about 30 mm protruding from the fish.

Fish were tagged with one TIRIS tag inserted in the dorsal midline just behind the head and two T-bar tags, one on each side just under the second dorsal fin so that the T-bar engages in the fin ray supports. Fish smaller than 400 mm total length have not been TIRIS tagged because it is thought that the tag makes too large a wound for fish this size to survive reliably. Most fish have also been injected with strontium chloride solution (approximately 80 mg Sr per kg of fish) to mark their otoliths for later verification of the age-reading process.

Fish for tagging were randomly selected after the catch was dumped into the pounds from the trawl net. The chosen fish were placed in a tank of circulating seawater for about 30 min to allow them to recover and to check for signs of morbidity. Any fish not considered to be in good enough condition for tagging were replaced with further randomly selected fish from the pounds. Fish were then weighed, measured, tagged and injected with strontium solution before being returned to the tank for a 30 min recovery period before being released through a scupper in the factory just above the waterline of the vessel. Generally, hauls with a fairly small catch (2 tonnes or less) were used to collect fish for tagging as the physical damage to the fish was minimised. In some cases special trawls were made to collect fish for tagging. An examination of length frequencies showed that size distribution of tagged fish was similar to that of the commercial catch.

Recaptures were monitored by a TIRIS detector placed over the conveyor between the fish pounds and the processing area. Factory crews were trained to look for the fish bearing T-bar tags and were given incentives to report recaptures to the observer. Recaptured fish were again weighed and measured. If they were in sufficiently good condition they were re-released, but otherwise the sex and gonad condition were noted and the otoliths removed. Some recaptures were not detected until after the head, tail and guts had been removed during processing.

Notifications were sent to French and South African authorities requesting that they advise their fishing vessels operating in the Kerguelen, Crozet and Prince Edward and Marion regions of the tagging program, and to look out for tagged fish.

From data on numbers of fish caught and numbers of tagged fish released and recaptured, estimates of available abundance were made for ground B using a Petersen approach, which states that, under ideal conditions, the proportion of tagged fish in the population should equal the proportion of recaptured fish in the catch. Applying this principle, estimates of the available abundance or the expected number of recaptures, given an estimated number of fish in the population, can be made. This is the basis of the assessment model developed by Tuck et al. (2002) from an original concept of de la Mare and Williams (unpublished data) that is applied here.

This model uses the exact time of release and recapture of tagged fish to estimate that portion of the total abundance that is available to the fishery. The model takes account of the fact that fish released earlier in the season have a higher likelihood of recapture (within a particular season) than fish tagged later in the season. The population models of the assessment include dynamics of tagged and untagged fish, allowing for natural and fishing mortality, net recruitment, growth and daily releases and recaptures. It is assumed that there is neither recruitment nor emigration during the fishing season (1 December to 30 November). The parameters estimated by the model are the pre-tagging available abundance N_0 and the annual net recruitment R_y (defined as the net change in available abundance between seasons). The potential impact of illegal, unregulated and unreported (IUU) fishing on the results has not been directly taken account of in this model. However, the loss of fish to IUU fishing would be indistinguishable, as far as the model is concerned, from migration, and will therefore appear as another factor within the net recruitment term (which includes juvenile recruitment and migration effects).

Fish caught in the HIMI trawl fishery generally fall between lengths 450 mm to 1 000 mm (Constable et al., 1999), as fish vulnerability at Heard Island decreases with length because, it is believed that adults inhabit deeper water than recruited juveniles, outside the range of the fishery. The dome-shaped vulnerability functions estimated by Constable et al. (1999), and applied in this assessment model, allow for decreasing availability of larger and older fish. The assessment model then assumes that the likelihood of recapturing a tagged fish of a given size is proportional to the vulnerability to fishing of that size class. Consequently, every released fish is aged using its recorded release length and estimates of von Bertalanffy parameters (L_∞ = 2 465 mm, k = 0.029 year^{-1}, t_0 = -2.56; data from SC-CAMLR, 2001). The tagged fish then grow each day according to the growth curve and, using the vulnerability function, the daily expected number of surviving available tagged fish is calculated.

The expected number of recaptures on any particular day can be calculated using daily catch numbers, the expected number of surviving available tagged fish, an estimate of available numbers of untagged fish, and the detection rate of recaptures. A Poisson distribution for the number of observed recaptures is assumed. By comparing observed recaptures with those expected from numerous iterations of the population model (varying parameters N_0 and R_y), maximum likelihood estimates of pre-tagging numbers of fish and net recruitment can be found.

As some uncertainty exists regarding the magnitude of natural mortality, M, two values covering the range of potential estimates are used to illustrate the sensitivity of the model to natural mortality. The chosen values are M = 0.1 and M = 0.16 (SC-CAMLR, 2001).

As tagged fish are released in a group, they may not immediately mix with untagged fish. This can cause a bias in parameter estimates. To account for this, the model allows a period of time for tagged fish to fully mix with the untagged population, δ days. For tagged fish recaptured within δ days of release, both the release and recapture event are removed from the analysis. Parameter estimates were not sensitive to δ over the wide range of values explored. However, the larger the value of δ, the less tagged fish remain in the analysis for estimation of parameters (and hence greater uncertainty in the estimates). A value of δ = 10 is used in this analysis.

While released fish have been tagged with both plastic and electronic tags, not all of these fish will be detected on recapture. Unfortunately, the electronic detector has not always been functional and visual spotting is not perfect, so some tagged fish escape detection. An estimate of the tag detection rate ω can be made when both visual detection and the electronic tag detector are functional. A detection rate ω_{vis} based only on visual spotting of tags can also be calculated using this method. Noting that ω does not apply outside the period when both detection mechanisms were functional, we have used the visual detection rate for all time periods, ω_{vis} = 0.9395. As this will be lower than the overall detection rate it can be seen as a conservative estimate. Sensitivity to the application of this rate was considered by applying the joint detection rate over all time periods, ω = 0.9732. Minimal changes to results were found.

Trends in stock numbers were combined with outputs from the assessment process for this stock at CCAMLR in 2001 (SC-CAMLR, 2001). This assessment uses the Generalised Yield Model (GYM) (Constable and de la Mare, 1996), which is a Monte Carlo simulation tool that allows for assessments of yield to be integrated across uncertainties in the population parameters. A simple population model, which includes estimates of recruitment and its variability, is run hundreds of times with values for growth, mortality and abundance drawn at random from suitable statistical distributions, to allow natural variability in the population as well as uncertainty in the parameter estimates to be incorporated. Thus, the simulation model is used to calculate a distribution of possible population sizes both in the absence of fishing and under various harvest scenarios.

Each of the many simulations starts with a biomass and stock structure of toothfish drawn from the recruitment function, which is derived from the time series of recruitments of age 4 fish estimated for HIMI since 1986. In each simulation year, the biomass is recalculated by adding an amount for annual growth and deducting an amount corresponding to natural mortality. The biomass of each year's recruits is added and the constant annual catch is deducted. Variability in the simulated population biomass in each year arises because the recruitment varies from one year to the next. Annual recruitment is applied according to known estimates of recruitment for a given year or, in the absence of such estimates, drawn from a lognormal statistical distribution derived from the time series of recruitments.

The current structure of the GYM and the parameters used in the modelling of the toothfish stock at HIMI are detailed in SC-CAMLR (2001). The estimates of recruitment since 1986 along with their uncertainty are important parameters included in these simulations. The known catch history is also included. The number of fish in the population is monitored each year of each of 1 001 trials. Box and whisker plots are used to illustrate the median expectation of the numbers of fish in the population in each year.

RESULTS

Placement of Tagged Fish

About 1 000 fish have been tagged each season since May 1998. Most fishing occurs in three well-defined grounds on the slopes of the Heard Island Plateau, and most of the tags have been placed in these grounds where the fishing depth is between 450 and 700 m. Fishing grounds A, B and C comprise areas of 412, 880 and 288 km^2 respectively in a total area less than 1 000 m deep of 93 111 km^2, so most of the tagging and recapture effort has been concentrated in a small fraction of the total area available to the fish. As opportunity permitted, however, fish have also been tagged on the shallower parts of the plateau (depth 300–500 m) to investigate the area from which these predominantly small fish (less than 400 mm total length) are recruited to the fishing grounds. The numbers of tags placed in each area and the number of recaptures for the period May 1998 to December 2001 are summarised in Table 1.

Estimated Tag Loss Rate

On recapture, the number of T-bar tags remaining on the fish has been noted in most cases. As all fish were double-tagged, the number of recaptures where only one tag remained gives an indication of the tag loss rate. Of 682 fish observed, 79 or a proportion of 0.1158 had lost one tag. Using the model of Xiao (1996), which takes into account the likelihood that fish recaptured after a short time at liberty will have had less opportunity to lose a tag than those at liberty for a long time, the proportion of fish that have lost one tag indicates that the probability of losing both tags after one year at liberty is approximately 0.01.

Movement

Figure 2 shows the distance moved between release and recapture plotted against time at liberty. This plot includes all but four of the 738 fish recaptured and it is clear that fish rarely move more than about 15 n miles from their point of release, despite having been at liberty for up to 3 years. All fish have been recaptured in the known fishing grounds (Table 1). As the fishing grounds are widely separated (ground A > 165 n miles > ground B > 123 n miles > ground C > 240 n miles > ground A) it follows that no fish have been observed to move between fishing grounds. The two fish that moved about 30 n miles (Figure 2) moved between ground B and the nearby shallow plateau, one in each direction.

In recent months, and contrary to the pattern of movement indicated by the abovementioned 734 recaptures, four fish have been recaptured in the French longline fishery in the Kerguelen and Crozet regions, several hundred nautical miles from their point of release. Table 2 gives the details of these four recaptures.

Table 1: Summary of the number of fish tagged and recaptured in each area by fishing season (1 December to 30 November).

Area	Number of Fish Tagged				Number of Recaptures			
	1997/98	1998/99	1999/2000	2000/01	1997/98	1998/99	1999/2000	2000/01
Fishing ground A	172			23	11	2		
Fishing ground B	558	707	778	1 155	22	107	204	306
Fishing ground C	237	50	510	187	39	13	9	25
Plateau shallow (<500 m deep)	14		306	120				
Plateau deep (500–1 000 m deep)	23		78	84				
Shell Bank	69		105	25				
Total	1 073	757	1 777	1 594	72	122	213	331

Table 2: Details of long-distance movements of tagged toothfish.

Date Released	Position and Depth of Release	Total Length at Release (mm)	Date Recaptured	Position and Depth of Recapture	Days at Liberty	Minimum Distance Moved (n miles)
13 May 1998	Ground B (575 m)	693	12 April 2001	Crozet (1 100 m)	1 065	1 033
4 May 1998	Ground A (369 m)	900	10 May 2001	Kerguelen (1 075 m)	1 102	210
11 April 1999	Ground B (570 m)	716	13 Sept 2001	Crozet (1 474 m)	917	1 025
28 May 2000	Ground B (600 m)	772	6 March 2002	Crozet (1 483 m)	647	1 030

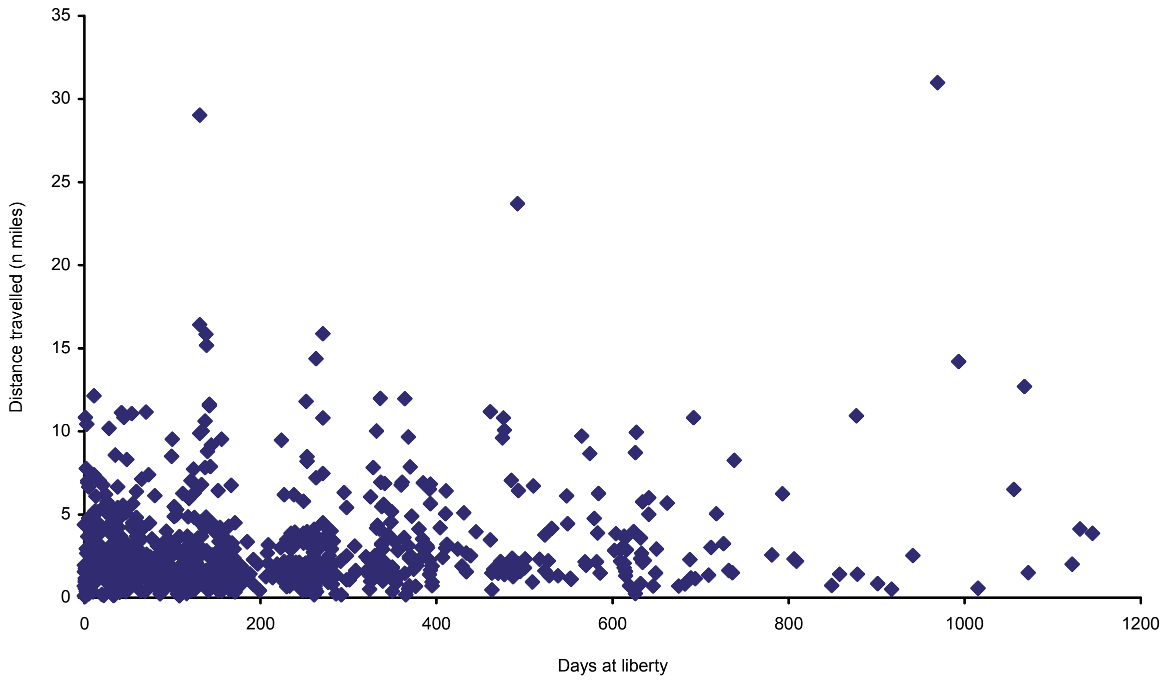

Figure 2: Distance moved and time at liberty of recaptured tagged fish in the Heard Island fishery. The four long-distance recaptures are not included.

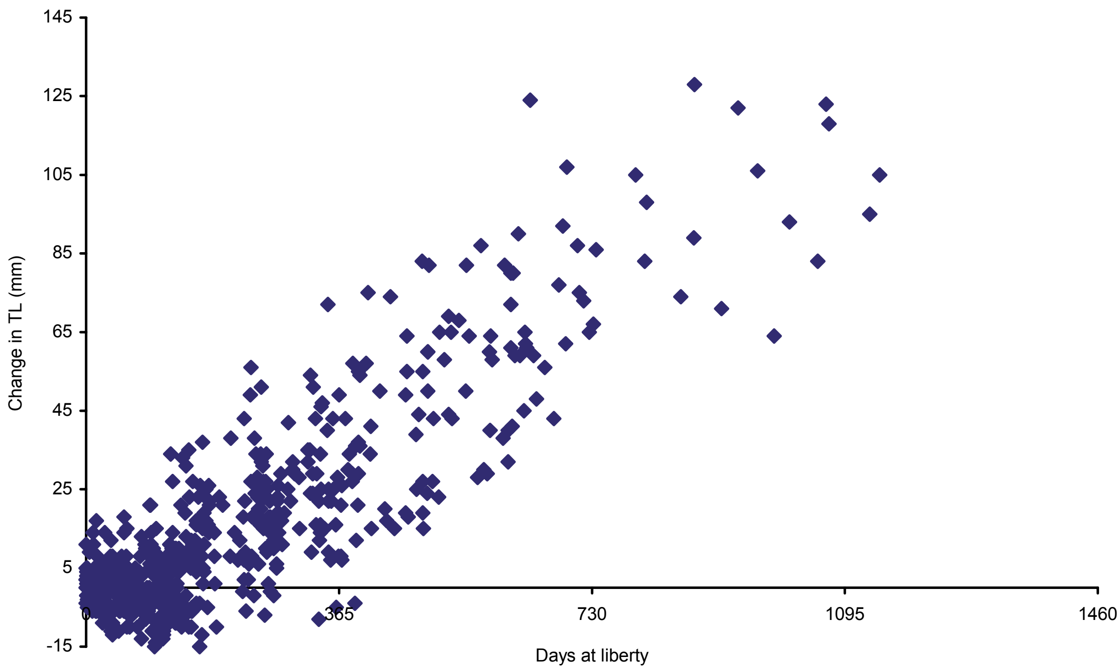

Figure 3: Change in total length of recaptured tagged fish in the Heard Island fishery.

Table 3: Growth data for tagged toothfish by size group.

Total Length at Release (mm)	Number of Fish	Slope of Regression	Annual Growth Increment (mm)	Standard Error
<600	25	0.13	49	6.21
600–650	34	0.13	49	5.99
650–700	34	0.12	44	5.48
700–750	39	0.10	38	4.93
750–800	15	0.14	50	12.08
800–900	21	0.11	39	6.68

Growth Rate

Figure 3 shows the difference in total length of fish between release and recapture plotted against days at liberty for the 570 fish that were able to be measured on recapture. During the first 180 days or so of liberty many of the recaptured fish apparently reduced in length by up to 15 mm. This could be the result of measurement error (although particular care was taken with measurement of tagged and recaptured fish), some result of the trauma resulting from the tagging process, or both. The rate of growth will also depend in part on the initial size of the fish. To investigate this further, fish that had been at liberty for 180 days or more were divided into groups according to their length at tagging and a regression fitted to the observed growth data for each length group. Results are summarised in Table 3.

Assessment of Available Abundance

Assessment of the initial abundance and subsequent net annual recruitment of toothfish from the tagging data was only attempted for ground B because of the relatively low number or sporadic nature of recaptures in the other grounds.

Figure 4 shows estimates of available abundance on 1 July (the reference day) of each year of the fishery in ground B with the 95% confidence limits (using the likelihood profile method) surrounding the point estimates. The results are not particularly sensitive to the applied natural mortality. Point estimates of available numbers decrease from approximately 7.5 million fish in 1998 to 3.5 million in 2001. It should be noted that these estimates lump different age groups of fish together, and so a continuous trajectory of available abundance over each season should not be inferred. This is because vulnerability has moved toward larger fish over the duration of the fishery (SC-CAMLR, 2001).

Predicted abundances of total fish from the projections using the GYM (Figure 5) show similar trends as for the results of the mark–recapture analysis, although the decline from 1998 to 2001 is not as great in those projections.

DISCUSSION

Given the number of returns, the length of time at liberty and the usually good condition of the fish on recapture, it is evident that the fish survive the tagging process well. This is despite the relatively rough treatment involved in trawl fisheries and the depth of the water from which they are taken. The low estimated rate of tag loss also confirms that tagging procedures are appropriate.

The movement data show two clear and contradictory trends. On the one hand the bulk of the data show that fish disperse only a very short distance, up to 15 n miles in most cases, from their point of release. This is perhaps unexpected given the length of time at liberty for some fish and the fact that toothfish are considered to be active benthic and mesopelagic predators (de Witt et al., 1990). Most of the fishing, and hence recapture effort, is concentrated in the established fishing grounds, so it is to be expected that the majority of recaptures will occur in these places. This concentration of effort should also result in a high probability of detecting fish movements between grounds, if they occur, but so far no such movement has been detected. All the fishing grounds are located on the slopes of the plateau in depths of 450 to 700 m so it appears that lateral movement parallel to the isobaths is uncommon. The main direction of movement is thought to be from shallow to deep water (Constable et al., 1999) whereby young fish are recruited to the fishing grounds from the shallow plateau and eventually pass on through the fishing grounds to deeper water, so that very few fish greater than 850 mm total length are caught in the fishery at grounds B and C. Thus it

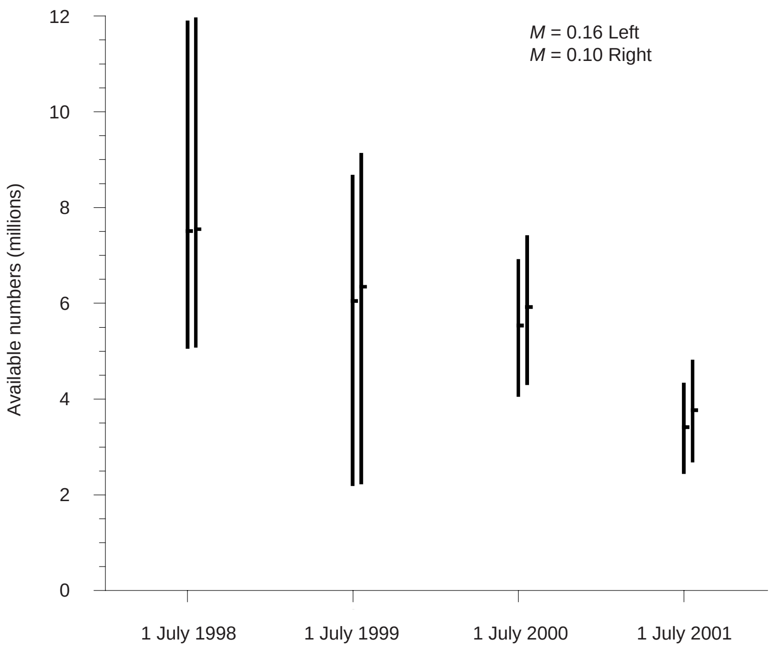

Figure 4: Estimated available numbers of fish with 95% confidence limits for ground B in the Heard Island fishery with 1 July as the reference day. Shown are results with M = 0.16 and M = 0.10, and δ = 10.

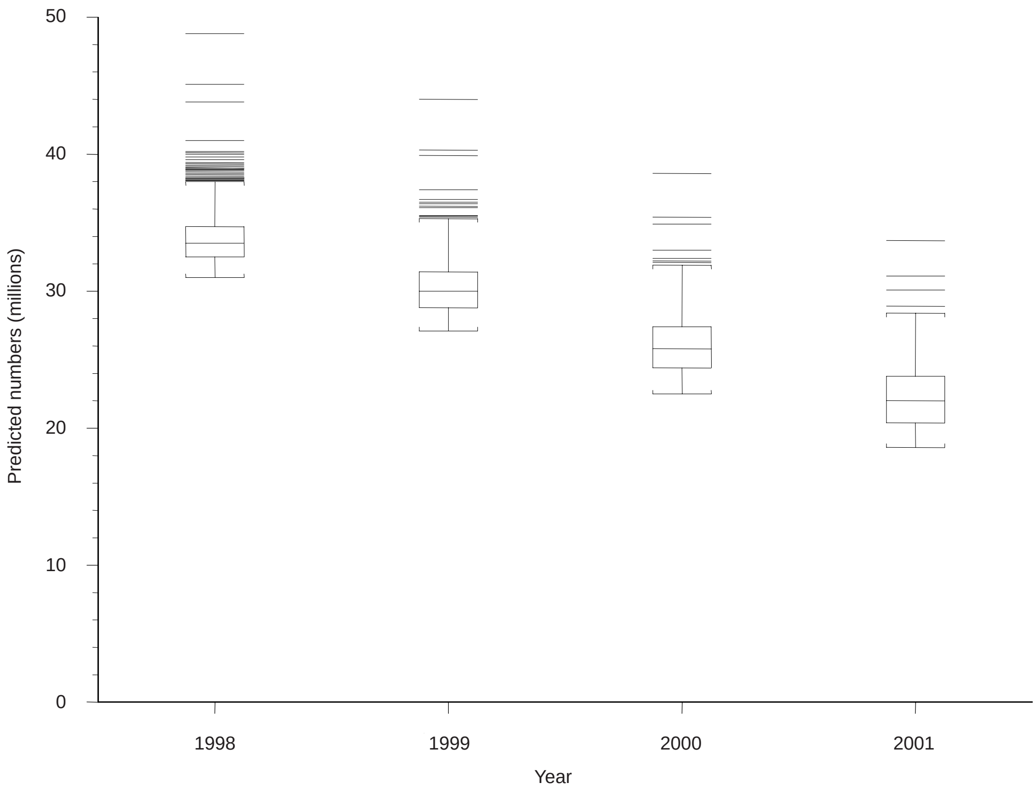

Figure 5: Box and whisker plots showing the time series of total numbers of fish (millions) at HIMI in 1 001 population projection trials using the GYM, based on parameters for HIMI toothfish used in SC-CAMLR (2001). For a given year in the trial period, each box shows the median value across all trials (the midline) and across the lower 25 percentile (the lower edge of the box) and the upper 75 percentile (the upper edge of the box). The whiskers show the primary range of data. The dashes indicate outliers.

appears that fish tend to be locally resident during the phase in which they frequent the depth range of the grounds. Any movement that may occur after passing through the grounds into (presumably) deeper water would therefore not be detected by the present pattern of fishing. Movement from the shallow plateau to the fishing grounds has not yet been detected although relatively few fish have been tagged on the plateau.

The movement patterns and recapture rates of fish in the Heard Island zone are similar to those around Macquarie Island, southwest of New Zealand, which is the only other locality where an extensive tagging program on toothfish has been undertaken. At Macquarie Island it was also found that very few recaptures were made in a different ground from the one in which they were tagged; of 4 564 fish tagged, 526 were recaptured, but only two of these had moved between the main fishing grounds, which in this case are only about 40 n miles apart (Williams and Lamb, 2001).

The four fish that moved a long distance provide contradictory evidence. The fact that three fish of a size normally caught in the upper slope trawl fishery (693–772 mm total length) were recaptured two to three years later in the French longline fisheries at 1 100 to 1 483 m depth (Table 2) suggests that the range of size at which the fish leave the trawl fishery grounds is wider than that estimated by Constable et al. (1999). These fish were not measured on recapture, but applying the growth rate in Table 3, the fish would have been in the range of approximately 825–922 mm total length on recapture. This implies either that the fish had left ground B at a total length considerably less than 850 mm, or that they were close to this size when they left the ground, but moved to their recapture location in a relatively short time. The fish that moved from ground A to Kerguelen was at the upper end of the size range normally found on the grounds. No tagged fish have been recaptured in the French trawl fishery near the Kerguelen Islands that is conducted in similar depths to the fishery at Heard Island. This fishery, however, ceased in June 2001, close to the time when the first long-distance recaptures were being taken in the longline fisheries. Other locations in the Indian Ocean sector where tagged fish could be recaptured are Prince Edward and Marion Islands and Ob and Lena Banks to the northwest and west of Heard Island respectively (Figure 1), or the Elan or BANZARE Banks to the south. No tagged fish have yet been recaptured in these locations. Although the numbers of tagged fish recaptured outside the Heard Island fishery is still too low to reliably establish any trends, they indicate at the moment that more fish than expected are moving to the Crozet Islands.

The four long-range movers provide the first documented direct evidence of toothfish moving such distances and of moving from one fishing area to another. We are confident of the veracity and accuracy of these recaptures because they were made by vessels licensed to fish in the areas where the recaptures were made and in the presence of observers, and were reported via government authorities. The fish moving to Crozet must have crossed a trough at least 390 n miles wide and over 4 000 m deep in transiting from the Kerguelen Plateau to Crozet. They will also have moved into very different oceanographic conditions, having originated at Heard Island, well south of the Polar Front, and ended up at Crozet, close to the usual position of the sub-Antarctic Front (Park et al., 1993). It would be interesting to know whether they had followed the bottom contours into very deep water or maintained what is regarded as their normal depth range by transiting through the mesopelagic zone. While evidence from four fish does not conclusively prove a migration pattern, it is likely that there have been more long-distance travellers than detected because the detection efficiency would have been lower on French vessels where crew members may have been less aware of the possibility of recapturing tagged fish and where TIRIS detectors were absent. Some tagged fish may also have been caught but not reported by IUU vessels in these areas. If this pattern of movement between Heard Island and Kerguelen and Crozet is confirmed by further recaptures, there will be far-reaching ramifications for the management of toothfish stocks in the Indian Ocean sector as the premise that Heard, Kerguelen and Crozet stocks are independent will have to be revised. Work planned for the near future on the genetics of toothfish from these three areas may provide some further insight.

The growth data from recaptured tagged fish are similar to the parameters used by Constable et al. (1999) based on age readings from otoliths. Both methods of growth estimation are subject to error; otolith reading is prone to sampling bias and error in interpreting annuli, and tagging programs can be biased by the effects of capture and tagging on the behaviour and physiology of the fish. It is thus reassuring that the two independent methods are in broad agreement and confirms that these data can be used in future analyses.

The estimates of available numbers of fish in ground B have declined steadily during the course of the experiment and are now at just under 50% of the value when the tagging program started. This method of stock assessment is only able to estimate *available* abundance (also referred to as *fishable* abundance). Available abundance is quite distinct from *total* abundance (as estimated by the GYM and shown in Figure 5) and *spawning* abundance which may be substantially more extensive, both spatially and in total magnitude. There are two factors which influence the available abundance: (i) *gear selectivity* (the probability of capture on encounter), and (ii) *availability* (the probability of encounter by the fishing gear). While gear type influences gear selectivity, oceanographic conditions and population movements can strongly influence the availability of fish. These two factors are generally functions of age or length, and can vary within and between seasons. In this paper the combined function of gear selectivity and availability at age is called the *vulnerability* function. The annual vulnerability functions for the Heard Island toothfish fishery were taken from Table 33 of SC-CAMLR (2001).

The influence of IUU fishing on the use of the Petersen equation to estimate available biomass is difficult to determine. The main effect of IUU fishing on the model will be the overestimation of the number of tagged fish remaining in the water. This would lead to an overestimation of available biomass. The total estimated IUU catch for the 1998/99 to 2000/01 split-years in the HIMI area is 2 609 tonnes (SC-CAMLR, 2001) which is 26.6% of the 9 795 tonnes of legal catch in the same period. Some of the IUU vessels have been sighted in or close to fishing grounds B and C, which suggests that some of their catch is from the same population as the legal catch. However, the proportion of catch taken in the same grounds as the legal fishery is not known. It can be expected that IUU catches of this magnitude will have an effect on the calculation of available biomass but there are insufficient data to estimate its magnitude.

The projections using the GYM and based on the time series of estimated annual recruitments of age 4 fish since 1986, indicate that the overall population may have changed in a similar way to the local stock at ground B. Ground B may have experienced a greater reduction in abundance than the overall stock because the fishery concentrates on the younger fish and it will be a few more years before the effects of the fishery are fully transmitted to the spawning stock. In addition, the greater catches from ground B as compared to other areas mean that the reduction in this area would be expected to be greater than for other areas and the stock as a whole.

The tagging experiment at Heard Island provides invaluable information about the dynamics of the fish inhabiting the area. The ability to estimate the available abundance using tagging data complements and further enhances the assessment methodologies (such as the GYM) already developed to manage the fishery. Tagging programs would be especially useful to provide available biomass estimates in areas where trawl surveys are difficult due to unsuitable bottom conditions or where the commercial fishery relies on longlining, thus making fishery-independent surveys impractical.

The tagging experiments in the HIMI fishery have also provided some useful insights into the biology of *D. eleginoides* and the fishery for this species, notably that the majority of fish do not move far from the ground in which they were tagged, at least while they are vulnerable to the current trawl fishery; and that a small but probably underestimated proportion of the population undertake extensive migrations across abyssal basins to other island groups. The program has also provided corroboration for estimates of growth and abundance of toothfish achieved by other methods.

The tagging program will continue at HIMI, providing a longer time series of data and more observations on the movements and growth rate of fish. Some of the questions raised by the results to date will also be further investigated. These include analysis of DNA of toothfish from Kerguelen, Crozet and Prince Edward and Marion Islands to test whether there is sufficient interchange of fish between the island groups to maintain genetic homogeneity. Implantation of archival tags recording depth and temperature will provide information on the vertical migration and feeding habits of toothfish.

This program may also offer opportunities for refining the assessment process because the trends in population numbers from the mark–recapture analysis are similar to the trends predicted from the GYM. With further development and validation, the mark–recapture analysis may be able to be used to statistically weight the population projections used in the GYM in the same manner as CPUE is used in refining the assessments for toothfish at South Georgia (Kirkwood and Constable, 2001).

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