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Updated analyses of tag return data from the CCSBT SRP tagging program

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Abstract

An updated summary of the data from the CCSBT SRP tagging program is presented, along with updated estimates of fishing mortality rates. SRP tagging was suspended in 2007, but the data and estimates can still be updated using tag returns that have occurred since the last report (Eveson and Polacheck 2008). A tag attrition model was again used to estimate cohort and age-specific fishing mortality rates for different groups of tag releases conditional on estimates of natural mortality, tag shedding and reporting rates (the latter three derived from separate analyses).

The results show very high estimates of fishing mortality rates (many over 0.5) in 2003 to 2007 for fish of ages 3 to 5 based on fish tagged at age 2 and 3. More encouraging is that the age 3 to 5 estimates for 2008, as well as the age 3 estimate for 2007, are somewhat lower (between 0.25 and 0.3). These results hold true for a range of scenarios using alternative reporting rate estimates for the surface and longline fisheries and alternative natural mortality rate vectors. Comparison of these results with those from the 1990s RMP tagging indicates that the fishing mortality being experienced by tagged fish has substantially increased compared to the early 1990s.

There continues to be a marked lack of returns, and thus lower estimates of fishing mortality, from fish tagged at age 1 compared to those tagged at ages 2 and above. This phenomenon was not observed in the tag returns from the 1990s releases, and suggests that 1-year-old fish found in WA (where the majority of age 1 fish are tagged) are no longer entering the GAB in substantial numbers. These same 1-year-old fish do not appear to be entering the longline fisheries either. Furthermore, the spatial distribution of longline returns from the 2000s tagging consistently show a much smaller percentage of tagged fish moving into the Tasman Sea in recent years than in the 1990s. These spatial changes have now been observed for 7 years (since 2001), suggesting that they are not simply outliers.

Changes in the exploitation rate estimates and spatial patterns of returns between the 1990s and 2000s suggest possible negative consequences in terms of current stock status (e.g. increased exploitation rates and possible range contraction). Only through continued and improved tagging experiments can the longer term consistency, implications, and underlying sources of these observed changes be understood. As such, it would seem critical that a large-scale tagging program be resumed and improved.

Introduction

As part of the Scientific Research Program (SRP), the CCSBT initiated a large-scale tagging program to estimate juvenile fishing mortality rates beginning in 2000/01 fishing season. The basic design of the tagging program was similar to that conducted in the 1990s as part of the CSIRO/NRIFSF Recruitment Monitoring Program with the aim to tag multiple cohorts at different ages in several years. This paper provides an updated analysis of the data collected to date in the SRP tagging program, including some estimates of fishing mortality rates obtained using the same approach as in the past four years (Polacheck and Eveson 2005, 2006, 2007; Eveson and Polacheck 2008).

Methods

Much of the Methods section remains unchanged from previous reports (Polacheck and Eveson 2005, 2006, 2007; Eveson and Polacheck 2008), but it is repeated here in full for easy reference.

Data

Tagging in the first year was only done off Western Australia (WA) with 1 and 2 year old fish being tagged. In all subsequent years, tagging was conducted in both WA and South Australia (SA) with almost all of the fish tagged being between ages 1 and 3 (i.e. less than 2% of the fish tagged are estimated to be older than age 3).

Some of the release and return data are considered unreliable for estimating mortality rates; therefore we applied the following screening process to the data prior to analysis.

For the release data:

- Only fish released into the wild were included (i.e., we excluded data from fish that were released into farms as part of a tag seeding program).
- Only releases where the fish was caught by pole and line were included. This method of catching fish is least likely to cause lasting injury to the fish.
- Only releases for which both tags were recorded as being inserted correctly were included to reduce the chance of tag shedding biasing our analyses.
- Only fish for which the injury due to tagging was regarded as slight were included to reduce the chance of fish mortality due to tagging biasing our analyses.
- Only fish whose length was recorded at the time of tagging were included because our analysis uses age of release, which is estimated based on length.

For the recapture data:

- Only recaptures corresponding to releases that met the above release criteria were included.
- Only recapture records from fish caught in the wild were included. For tagged fish that are harvested from the farms, the database has two records: one corresponding to the original capture from the wild and one corresponding to the harvest from the farm. For the purposes of estimating fishing mortality we are only interested in the information (date and location) for the capture from the wild.

A fish's age at tagging was estimated from its length using cohort slicing and the growth curve currently adopted by the CCSBT (Anon. 2001). SBT grow rapidly as juveniles so there is good separation between length distributions at the ages being tagged, and therefore the number of aging errors should be small. All tagging was done between December and April, so the release ages were adjusted in order that fish tagged in December from a given year-class/cohort were assigned the same age as those tagged after December. The recapture age was calculated using the age of release and the time between release and recapture. Recapture ages were also adjusted so that fish from a given cohort caught in November or December were given the same age as those caught after December.

As discussed below, results from separate analyses of tag shedding rates preformed by Dr. W.S. Hearn (CSIRO Marine and Atmospheric Research) are used in the estimation of mortality rates. In addition to the above data screening, Dr. Hearn excluded tag returns if the recapture year or month within year was uncertain, or if the day within month was uncertain for recaptures at liberty less than 270 days. Also, data sets associated with a tagger were only analysed if there were 30 or more acceptable recaptures in the set. Data associated with the remaining taggers were pooled into a set we call "tagger" ZZ.

The data used in this paper were taken from the most recent version of the CCSBT tag database (2009-04-09) at the time of analysis.

Estimation Model

A basic tag attrition model was used to estimate cohort and age-specific fishing mortality rates for different groups of tag releases. This model was chosen because it provides a direct estimate of the fishing mortality rate for those fish tagged independent of any assumptions about mixing. This is seen as a first step to evaluate the consistency of estimates from different releases prior to developing a more integrated estimation model (e.g. a Brownie model).

We define two seasons: season 1 runs from January 1 to June 30 and corresponds to the Australian surface fishery; season 2 runs from July 1 to December 31 and corresponds to the longline fishery. For convenience, the model assumes all releases occurred in season 1 on January 1. In addition, the model follows the convention used in the CCSBT Management Procedure operating model in which all fishing is assumed to occur either on January 1 (season 1) or July 1 (season 2). All returns from the Australian surface fishery were assumed to occur in season 1 and all longline returns were assumed to occur in season 2. Natural mortality is assumed to occur at a constant rate throughout the year (i.e., it is evenly split between the two seasons since they are of equal length).

Because there are two seasons per year, it is convenient to work in terms of time periods taking values $t = 1, 2, 3, \ldots$, where season 1 corresponds to odd time periods, season 2 corresponds to even time periods, and a year consists of a consecutive odd and even time period.

Let

$$N_{c,a,g,t+1} = (N_{c,a,g,t} - \widehat{R}_{c,a,g,t})e^{-0.5m_{a*}} \tag{1}$$

where

$N_{c,a,g,t}$ = the number of tagged fish alive at the start of time period *t* from fish tagged from cohort *c* at age *a* by tagger group *g*;

$\widehat{R}_{c,a,g,t}$ = the estimated number of tagged fish caught in time period *t* from fish tagged from cohort *c* at age *a* by tagger group *g*;

m_{a*} = natural mortality for fish of age $a* = y - c$, where *y* denotes the year corresponding to time period *t*.

The subscript *g* in the above equation is necessary if one wishes to examine results for different groups of taggers. This could be all taggers, a group of a few taggers, or a single tagger. In the current paper, we only present results using all taggers, but in past we have compared results for different groups of taggers (e.g. Polacheck and Eveson 2007).

The number of recaptured tagged fish, $\widehat{R}_{c,a,g,t}$, in equation 1 is not simply the number of tags actually returned but is estimated to take into account both tag shedding and non-reported tags. Specifically, $\widehat{R}_{c,a,g,t}$ is estimated by

$$\widehat{R}_{c,a,g,t} = \frac{\sum_{k \in g} \left(R_{c,a,k,t} / \gamma_{c,a,k,t} \right)}{\lambda_t}$$

where

$R_{c,a,k,t}$ = the actual number of reported tag returns in time period t from fish tagged from cohort c at age a by a tagger in sub-group k of tagger group g;

$\gamma_{c,a,k,t}$ = the probability that a fish tagged from cohort c at age a by a tagger in sub-group k has at least one tag still attached at the beginning of time period t;

λ_t = the tag reporting rate in time period t.

Recall that all fish have been double-tagged. The probability of a tagged fish still having at least one tag attached at the time of capture,
$\gamma_{c,a,k,t}$, is given by

$$\gamma_{c,a,k,t} = 1 - \left[1 - Q_{a,k}(\tau)\right]^2$$

where

$Q_{a,k}(\tau)$ = the probability of a tag still being attached to a fish tagged at age a by a tagger in sub-group k after the fish has been at liberty for time τ. Note that τ is a function of c and a (which together define the time period of release) and t (the time period of recapture).

Finally, an estimate of the annual fishing mortality rate in year y, corresponding to time periods t and t+1 (where t is odd), for fish from cohort c (i.e. age $a^* = y - c$) can be calculated from the ratio of the estimated number of tagged fish alive at the start of year y+1 (time period t+2) to the estimated number of tagged fish alive at the start of year y (time period t). A separate value can be calculated corresponding to fish tagged at age a by a tagger in tagger group g. Thus,

$$f_{c,a,g,y} = -\left[m_{a^*} + \log\left(N_{c,a,g,t+2} / N_{c,a,g,t} \right) \right]$$

Bootstrap confidence intervals for $f_{c,a,g,y}$ were calculated by sampling the releases at age a from cohort c by tagger group g along with the associated recapture data with replacement and calculating the estimates of $f_{c,a,g,y}$ for each bootstrap sample. The confidence intervals presented are based on 1000 bootstrap replicates and treat each tag release as independent.

This may underestimate the actual uncertainty if releases from the same school tend to stay together. The bootstrap estimates are also conditional on the estimates of reporting rates, shedding rates and natural mortality rates.

Reporting Rates

Estimates of the reporting rate in the Australian surface fishery are available for the fishing seasons ending in 2003 to 2008 from tag seeding experiments conducted in these years (Hearn et al. 2009). The estimates declined steadily from 0.64 in 2003 to 0.30 in 2006, but have increased over the past two years to 0.53 in 2008 (Table 1, vector A1). The low estimates in recent years can yield unrealistically high values for some fishing mortality rates, and has raised the question of whether in fact the tag seeding results are providing unbiased estimates of the reporting rate (Polacheck and Eveson 2007). Hearn et al. (2009) further discuss this issue and suggest a number of alternative reporting rate vectors for consideration (Table 1, vectors A2-A5). Brief descriptions of the alternative reporting rate vectors are as follows:

A1. "Best estimates" from the tag seeding results.

A2. Assumes that the reporting rate in 2003 was 1.0 and that the difference between the estimate of 0.64 from the tag seeding was due to high initial shedding of both tags (i.e. a lack of independence in shedding) associated with tagged fish being in cages. Further assumes that the rate of high initial shedding is constant across years and re-adjusts the other reporting rates accordingly.

A3. Estimates based only on Tagger 4; the most consistently used tagger and also one with extensive experience.

A4. Assumes reporting rates have been constant and uses the rate of return from the re-release of wild tagged fish from the 40 fish samples as an estimate of the reporting rate (see Polacheck and Eveson 2007 for details).

A5. Assumes reporting rates were the same in 2003 to 2004 and 2005 to 2008 and uses the rate of return from the re-release of wild tagged fish from the 40 fish samples for these two periods to estimate the reporting rates.

Insufficient information was available to estimate reporting rates from the longline fisheries. Estimates of reporting rates from longliners were substantially below those in the surface fishery in the 1990s. Reporting rates for Japanese longliners in the 1990s ranged from 0.07 to 0.49 (Eveson and Polacheck 2005). There were no data to directly estimate reporting rates for Taiwanese vessels. In the absence of any direct data, results were explored for two values, namely 0.65 and 0.30, to provide an indication of the sensitivity of the results to the value assumed. The same value was used for all ages and years. Note, however, that unless the reporting rates were the same in the different longline fleets, the reporting rate would in fact vary with age and year even if the reporting rate was constant over time within a fleet; this is because the proportion of the total longline catch of a given age class by a given fleet varies among years (Pollock et al. 2002).

Tag Shedding

Tag shedding rates provided by Dr. Hearn were based on an analysis of the tag shedding data (number of recaptures with one tag versus two tags still attached) for taggers who participated in the SRP tagging program. Dr. Hearn applied the method of Kirkwood and Walker (1984) to estimate shedding parameters. The retention function (i.e., the probability of a tag still being attached after being at liberty for time τ) was assumed to have the form

$$Q_{a,k}\left(\tau\right) = \xi_{a,k} \exp\left(-\Omega_{a,k}\tau\right)$$

where $\xi_{a,k}$ is the fraction of tags immediately retained (i.e. $1 - \xi_{a,k}$ are immediately shed) for fish tagged at age a by a tagger in sub-group k, and $\Omega_{a,k}$ is the continuous shedding rate. The model allows for tag shedding to vary between tagger groups (which may be individual taggers) and between fish released at different ages. The retention function was assumed to be the same for both tags on a given fish. Table 2 provides the estimates of the parameters for this retention function when fitted to the SRP tag return data. This table provides estimates for individual taggers as well as for groups of taggers which do not differ significantly in their tag shedding parameters. Only the estimates for the groups of taggers are used in the estimates of fishing mortality rates presented here, but the results are very similar if estimates for individual taggers are used. In the notation above, each set of taggers constitutes a potential sub-group k.

In Polacheck and Eveson (2005), we also considered the potential effect of age-specific shedding. There were only sufficient data to meaningfully perform these calculations for two taggers. Only for one of these was the difference significant and the differences had only a minor effect on the overall results. As such, we have not subsequently updated these estimates.

Natural Mortality Rates

Two age-specific natural mortality rate vectors were used in the calculation of the fishing mortality rates (Table 3) to provide a measure of the sensitivity of the estimates to assumptions about natural mortality. These are two of the vectors used in an early version of the SBT Management Procedure operating model.[1]

Results and Discussion

Table 4 provides an updated summary of the number of releases and recaptures by cohort. Note that it was decided at the 2007 CCSBT SAG and SC meetings to suspend the conventional tagging program; thus, only a small number of juvenile SBT have been tagged since then as part of field exercises for other research programs. Note that the percent returns for recent cohorts will increase over the next few years as tags continue to be returned from fish at older ages. Given the current fisheries, only significant numbers of recaptures are expected from fish ages 3 and older. Since most of the returns from this year's Australian surface fishery are not yet available, the tagging data are not yet informative for releases from the 2006 and 2007 cohorts. As such, the focus of the results presented are for the 1999-2005 cohorts (the number of releases for the 1998 cohort are too small to provide meaningful results).

[1] The operating model (OM) has undergone a number of iterations since that time, and in the most recent version (July 2009), natural mortality is assumed to follow a specific functional form with some parameters fixed at a range of values and others estimated in the model. The analysis in this paper was redone using a few of the natural mortality vectors from the latest OM, but the F estimates and general conclusions remain the same as those presented.

Table 5 provides a breakdown of the release and recapture data by cohort, age at release and age at recapture. As noted in previous years, the percent of returns from fish released at age 1 tends to be very low compared to fish released at ages 2 and 3 from the same cohort. This was not observed in the 1990s RMP tag returns, but continues to be a persistent feature of the SRP tag returns; possible reasons were explored and discussed in Polacheck and Eveson (2007).

Location of Longline Returns

It has become evident in recent years that the proportion of longline tag returns coming from the Tasman Sea has been much lower in the 2000s compared to the 1990s (Table 6). As discussed in Polacheck and Eveson (2007), this in part reflects changes in the spatial distribution of fishing effort within the Tasman Sea. In particular, a substantial fraction of longline fishing effort occurred in the Australian Fishing Zone (AFZ) in the 1990s as a result of joint venture operations and bi-lateral access arrangements that allowed vessels to fish within the AFZ (Table 7). These arrangements ceased in 1998 and thus there has been little recent fishing effort in the areas where substantial numbers of the 1990s returns came from. However, it seems unlikely that these factors are sufficient to explain the large differences in the spatial distribution of longline returns in the 1990s compared to the 2000s (refer to Polacheck and Eveson 2007 for a detailed discussion).

Fishing Mortality Rate Estimates

Sufficient release and return data (e.g. at least ~400 releases at a particular age and at least one year of full recoveries) exist to derive age-specific fishing mortality rate (F) estimates for cohorts 1999 to 2005 tagged at ages 1 to 3 (with the exception of cohort 1999 at age 3). Table 8 contains the age-specific F estimates, along with bootstrapped 90% confidence intervals, obtained using reporting rate vector A1 from Table 1 for the surface fishery, group shedding rate parameters from Table 2, natural mortality vector 1 from Table 3, and a reporting rate of 0.65 for the longline fisheries. It should be noted that estimates of fishing mortality rates based on returns from the same year of release (e.g. the F estimates for age 2 based on age 2 releases) can be highly misleading in terms of being representative of the fishing mortality experienced by a cohort because the releases may have occurred before, during or after the main period of fishing, and the distribution of releases would also affect the number of returns. However, they do provide a measure of the fishing mortality rate experienced by the set of tagged fish and in this sense can still be informative. For this reason, they are still included in Table 8 but they are italicized to as a reminder that they need to be interpreted carefully.

Some high F estimates are evident in Table 8. In particular, fishing mortality rates at ages 3 and above tend to be high for fish tagged at age 2 and older, with many estimates above 0.4 (see also the estimates for the 2000s in Figure 1). In a few cases, the estimates seem unrealistically high (e.g., greater than 1.0). For age 3 fish in 2007 and age 3 and 4 fish in 2008, the F estimates are somewhat lower (ranging from 0.27 to 0.38).

Also evident is that the F estimates for ages 3 and above for fish tagged at age 1 are markedly lower than the 'equivalent' estimates from fish tagged at older ages (i.e., F estimates for a given recapture year and age are much lower when estimated using releases at age 1 than when estimated using releases at ages 2 and above.) This anomaly has been noted in past and was discussed in detail in Polacheck and Eveson (2007). As such, we will not repeat the discussion here except to say that the reason for this inconsistency has not been resolved.

Table 9 provides a comparison of estimates of fishing mortality rates for a range of scenarios. Specifically, scenario 1 contains the estimates from Table 8, as described above. Scenarios 2-4 are the same as scenario 1 except: scenario 2 uses reporting rate vector 4 from Table 1 for the surface fishery; scenario 3 uses a reporting rate of 0.30 for the longline fisheries; and scenario 4 uses natural mortality vector 2 from Table 3. As would be expected, the estimates are somewhat higher with a lower reporting rate for the longline fishery (scenario 3) and with higher natural mortality rates (scenario 4). The estimates for scenario 2 compared to scenario 1 can vary since reporting rate estimates are higher for A4 than A1 in some years and lower in others. Overall, however, the very high and, in some cases, seemingly "unrealistic" fishing mortality rate estimates are evident for all scenarios.

Figure 1 compares estimates of fishing mortality rates for ages 3, 4 and 5 obtained from the SRP tagging with those obtained from tagging experiments conducted in the 1990s as part of the collaborative CSIRO-NIRFSF Recruitment Monitoring Programme (RMP). The general tagging locations and methods of tagging were the same between decades; as such, Figure 1 should provide a valid comparison of the estimates between these two periods. For the SRP data, F estimates are shown for different ages of release (excluding estimates that are for the same age as the age of release). The RMP estimates for the 1990s have been calculated in two ways: 1) using the same methods applied to the SRP data; and 2) based on a Brownie estimation model that integrates data from all release ages (estimates taken from Table A1 of Eveson et al. 2006). In the case of 1), the reporting rate for the surface fishery was assumed to be 0.81 in all years except 1996, for which mass deaths in the farms results in a reduced reporting rate of 0.43. These estimates are taken from Table 2 of Eveson and Polacheck (2005), and are based on tag seeding experiments that took place during the 1990s. The same reporting rate value for the longline fishery and the same natural mortality rate vector was used for the 1990s as was used for the 2000s. In the case of 2), the mortality rates were estimated within the Brownie model, and the reporting rates and shedding rates differed slightly (see Table 1 of Eveson et al. 2006 for exact values); however, the results should still be comparable to those obtained from 1).

Evident in Figure 1 is that the F estimates for a given year and age derived from different ages at release were consistent within the 1990s. This is in contrast with the 2000s, for which the F estimates derived from age 1 releases are much lower than those derived from age 2 and 3 releases, and even the estimates from the age 2 and 3 releases are not as consistent as in the 1990s. Because of the consistent nature of the 1990s data, a Brownie model, which combines data from all release ages to come up with a single F estimate for each year and age of recapture, is an appropriate and more powerful method to apply. However, it is not appropriate to apply to the 2000s data unless the reason for inconsistencies between release ages can be identified and accounted for.

Also evident in Figure 1 is that the fishing mortality being experienced by the tagged fish is substantially greater in the 2000s than it was in the 1990s, particularly for age 4 and 5 fish. While interpretation of the differences are confounded by the relatively lower return rates from age 1 releases compared to older ages in the SRP tagging noted above, the results suggest that juvenile exploitation rates at ages 3 to 5, at least for fish found within the GAB, have increased substantially and to high levels. The estimates for the 2001, 2002 and 2003 cohorts based on age 2 releases are very high (i.e. >0.5). This would be consistent with other indicators suggesting that these cohorts were unusually small. The F estimate at age 3 and 4 for the 2004 cohort and at age 3 for the 2005 cohort based on these same age 2 releases has decreased, suggesting that these cohorts may be larger (or perhaps better mixed with WA fish). Nevertheless, these estimates are still quite high (~0.27), especially in comparison to the early 1990s.

Returns from the First Season for December Releases

Tag returns from releases near the beginning of the fishing season in the GAB can provide an indication of localized exploitation, particularly if tagging does not take place in the immediate vicinity of fishing operations. In 2003 to 2007, some of the SRP tagging operations took place in December in the GAB in inshore areas, whereas fishing operations were concentrated near the shelf edge. Over the next four months, tags were returned from 9%-38% of the age 3, 4 and 5 fish (Table 10). These recapture rates suggest high exploitation rates for fish found in the GAB in December, particularly after taking into account the estimates of reporting rates from tagging seeding experiments (final column of Table 10). The extent to which these represent global rates depends in part on the proportion of the age 3 to 5 fish that are in the GAB during the summer months.

Perhaps somewhat surprising in these data are the low levels of returns from age 2 fish tagged in the same location and time period (Table 10). Less than 5% of the fish tagged at age 2 were estimated to have been recovered during the fishing season in spite of the fact that there were sizable catches of 2 year olds in these years.

Summary

The updated results from an analysis of the tag-return data from the CCSBT SRP continue to show very high estimates of fishing mortality rates (many over 0.5) in 2003 to 2007 for fish of ages 3 to 5 (based on fish tagged at ages 2 and 3); however, the age 3 to 5 estimates for 2008, as well as the age 3 estimate for 2007, are somewhat lower (between 0.25 and 0.3). Comparison of the SRP tagging results with those from the 1990s RMP tagging indicates that the fishing mortality being experienced by tagged fish has substantially increased. While interpretation of the differences is confounded by the relatively lower return rates from age 1 releases compared to older ages in the SRP tagging, the results suggest that juvenile exploitation rates for age 3, 4 and 5 fish found within the GAB have increased substantially and to high levels. These high exploitation estimates have been seen consistently for the last five years, and even though the most recent estimates are not as high as in the preceding few years, they remain above levels experienced in the early 1990s.

A number of apparent anomalous features in the fishing mortality rates from the SRP tagging program were discussed in Polacheck and Eveson (2007). One such anomaly, which was noted again in this report, is the marked lack of returns (and thus lower fishing mortality estimates) from fish tagged at age 1 compared to those tagged at ages 2 and above—a phenomenon that was not observed in the tag returns from the 1990s releases. Other anomalies that were not discussed again in this year's report include: i) evidence of significant tagger effects, with tagger 1 consistently yielding somewhat higher fishing mortality estimates; ii) low estimates of fishing mortality rates at age 2, which appear inconsistent with the catch data from the surface fishery; iii) estimated number of tags returned per 1000 fish caught in the surface and longline fisheries also suggest inconsistencies with the catch data. These issues remain relevant and a full discussion can be found in Polacheck and Eveson (2007).

Comparison of the 1990s and 2000s tag returns also indicates substantial and unexplained changes in the spatial dynamics of juvenile fish. One year old fish found in WA are no longer entering the GAB in substantial numbers. These same one year old fish appear not to be entering the longline fisheries. These differences raise questions as to where these fish are going (or whether they are possibly dying at very high rates from natural causes). Furthermore, the spatial distribution of longline returns from the 2000s tagging consistently show a much smaller percentage of tagged fish moving into the Tasman Sea in recent years than in the 1990s. These changes have now been observed in five years of release and recovery data, suggesting that they are not simply outliers. The underlying cause for these differences is unknown. However, they would be consistent with either a density-dependent induced spatial contraction and/or environmentally driven changes in spatial distribution. Both of these, but particularly the first, would have implications for the stock assessment and advice on the effects of possible management actions.

The differences seen in the estimates of fishing mortality rates and the spatial pattern of returns between the 1990s and 2000s demonstrate the value and importance of the tagging experiments for providing insights into the status of the juvenile component of the SBT stock. The recent results raise a large number of unanswered questions as to the mechanism(s) underlying the changes. However, the changes suggest possible negative consequences in terms of current stock status (e.g. increased exploitation rates and possible range contraction). It seems that only through continued and improved tagging experiments that the longer term consistency, implications, and underlying sources of the observed changes can be understood. Cessation of tagging at this point will break the continuity of the time series of data that have been generated to date, and leave unresolved the persistence of the observed changes. It will also eliminate one of the few fishery independent (i.e. non-CPUE based) indicators for the stock assessments. For these reasons, it would seem critical that a large-scale tagging program be resumed as soon as possible in the format considered most viable and reliable (e.g., conventional tagging with improved mechanisms for estimating reporting rates, PIT tagging, gene tagging).

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Table 1: The set of five alternative reporting rate estimates (vectors A1 to A5) considered for the surface fishery, taken from Table 5 of Hearn et al. (2009). Reporting rates in 2001 and 2002, for which no tag seeding data exist, are assumed to be the same as in 2003. Note that year *y* refers to the fishing season ending in year *y*.

Year	A1	A2	A3	A4	A5
2003	0.64	1.00	-	0.47	0.67
2004	0.50	0.78	0.63	0.47	0.67
2005	0.40	0.63	0.34	0.47	0.39
2006	0.30	0.47	0.50	0.47	0.39
2007	0.43	0.67	0.47	0.47	0.39
2008	0.53	0.83	0.52	0.47	0.39

Table 2: Shedding rate estimates by individual taggers and by tagger groups, updated using data from CCSBT tag database version 2009-04-09 (results provided by Dr. W.S. Hearn, CSIRO Marine and Atmospheric Research).

	Tagger ID	Initial retention fraction (ξ)	Continuous shedding rate (Ω)	Recaptures with 2 tags	Recaptures with 1 tag	Total number recaptures
	2	0.980	0.108	2444	1135	3579
	4	0.860	0.142	1344	1298	2642
	418	1.000	0.183	52	59	111
	419	1.000	0.295	78	118	196
	444	1.000	0.179	72	65	137
	570	0.841	0.057	512	321	833
	1439	0.776	0.065	362	314	676
	1525	0.876	0.000	264	75	339
	1646	0.866	0.128	320	289	609
	ZZ	0.424	0.000	7	19	26
Tagger Group						
1	1525	0.876	0.000	264	75	339
2	2	0.980	0.108	2444	1135	3579
3	570	0.841	0.057	512	321	833
4	4+418+444+1439+1646	0.839	0.121	2150	2025	4175
5	419	1.000	0.295	78	118	196
6	ZZ	0.424	0.000	7	19	26

Table 3: Age-specific natural mortality rates used in the estimation of fishing mortality rates.

			Age		
Vector	1	2	3	4	5
1	0.3401	0.3028	0.2700	0.2420	0.2153
2	0.4202	0.3703	0.3278	0.2894	0.2538

Table 4: Total number of tag releases and reported recaptures (i.e. returns) by cohort (using data from the CCSBT tag database version 2009-04-09).

Cohort	Number releases	Number returns	Percent
1998	50	7	14.0
1999	1190	144	12.1
2000	5789	904	15.6
2001	9899	2112	21.3
2002	10307	1597	15.5
2003	14481	2824	19.5
2004	15154	1287	8.5
2005	17897	995	5.6
2006	4068	42	1.0
2007	14	0	0.0

Table 5: The number of releases by age and corresponding returns by age for the 1998-2006 cohorts (using data from the CCSBT tag database version 2009-04-09). Note that rows with less than 20 releases have not been included.

Cohort	Age at release	No. releases	No. returns by age								Total returns	Percent returns
			1	2	3	4	5	6	7	≥8		
1998	5	44					3	1	1	0	5	11.4%
1999	2	750		0	11	51	10	4	2	1	79	10.5%
	3	23			0	1	0	2	0	0	3	13.0%
	4	414				34	16	8	3	1	62	15.0%
2000	1	1921	0	4	88	19	4	2	1	0	118	6.1%
	2	492		1	50	37	14	1	2	1	106	21.5%
	3	3276			297	256	68	20	4	1	646	19.7%
	4	32				7	5	1	1	0	14	43.8%
	5	68					12	6	2	0	20	29.4%
2001	1	2748	0	9	129	19	7	4	0	0	168	6.1%
	2	5869		31	1093	285	81	10	8	0	1508	25.7%
	3	1146			253	104	42	8	3	0	410	35.8%
	4	135				12	10	2	1	0	25	18.5%
2002	1	3316	1	26	69	25	4	0	0		125	3.8%
	2	6256		90	708	361	124	11	1		1295	20.7%
	3	720			54	92	26	1	0		173	24.0%
2003	1	2662	0	33	154	71	4	0			262	9.8%
	2	8692		102	1231	587	59	0			1979	22.8%
	3	3127			244	299	38	2			583	18.6%
2004	1	7084	2	31	131	67	0				231	3.3%
	2	7591		69	529	370	4				972	12.8%
	3	479			35	49	0				84	17.5%
2005	1	9196	3	33	101	0					137	1.5%
	2	8699		117	739	2					858	9.9%
2006	1	4038	0	40	2						42	1.0%
	2	30		0	0						0	0.0%

Table 6: Percent of (reported) longline recaptures that occurred in the Tasman Sea (defined as east of 142°E).

		Age at recapture						
		2	3	4	5	6	7	8
1990s RMP	All longline returns	39.4	46.7	53.5	58.6	60.3	64.1	45.7
	Japanese returns	39.1	48.1	50.9	54.2	56.5	59.3	42.9
2000s SRP	All longline returns	10.9	7.5	8.1	3.3	15.6	13.6	0.0
	Japanese returns	28.9	19.8	22.0	5.9	23.5	20.0	0.0

Table 7: Percent of (reported) longline recaptures from the Tasman Sea (defined as east of 142°E) that occurred in the Australian Fishing Zone (AFZ) for the 1990s RMP tag releases.

	Age at recapture						
	2	3	4	5	6	7	8
% in AFZ	91.2	77.7	68.2	51.6	42.8	35.1	21.6

Table 8: Estimates of age-specific fishing mortality rates (F) for different cohorts derived from tags released in the waters around southern Australia. Results are presented separately for tags released at different ages. The 90% confidence intervals from the bootstrap estimates (i.e., the 5th and 95th percentiles) are also given. Results were derived using reporting rate vector A1 from Table 1 for the surface fishery, group shedding rates from Table 2, natural mortality vector 1 from Table 3, and a reporting rate of 0.65 for the longline fisheries. F estimates > 0.4 are shaded, and those derived from recaptures in the same year as release are italicized.

Cohort	Age at release	Number releases	Age	Year	Number recaps	F	5%	95%
1999	2	750	2	2001	0	*0.000*	*0.000*	*0.000*
			3	2002	11	0.036	0.019	0.056
			4	2003	51	0.255	0.197	0.328
			5	2004	10	0.095	0.048	0.155
2000	1	1921	1	2001	0	*0.000*	*0.000*	*0.000*
			2	2002	4	0.006	0.001	0.011
			3	2003	88	0.172	0.140	0.206
			4	2004	19	0.069	0.045	0.096
			5	2005	4	0.019	0.005	0.038
2000	2	492	2	2002	1	*0.004*	*0.000*	*0.011*
			3	2003	50	0.273	0.206	0.341
			4	2004	37	0.475	0.333	0.656
			5	2005	14	0.447	0.240	0.801
2000	3	3276	3	2003	297	*0.155*	*0.140*	*0.171*
			4	2004	256	0.282	0.250	0.314
			5	2005	68	0.153	0.119	0.186
2001	1	2748	1	2002	0	*0.000*	*0.000*	*0.000*
			2	2003	9	0.008	0.004	0.012
			3	2004	129	0.213	0.181	0.245
			4	2005	19	0.057	0.036	0.079
			5	2006	7	0.031	0.012	0.053
2001	2	5869	2	2003	31	*0.009*	*0.006*	*0.012*
			3	2004	1093	0.745	0.697	0.796
			4	2005	285	0.680	0.582	0.787
			5	2006	81	0.543	0.406	0.734
2001	3	1146	3	2004	253	*0.580*	*0.515*	*0.657*
			4	2005	104	0.797	0.626	1.004
			5	2006	42	1.530	0.823	3.149
2002	1	3316	1	2003	1	*0.001*	*0.000*	*0.002*
			2	2004	26	0.023	0.015	0.030
			3	2005	69	0.114	0.091	0.139
			4	2006	25	0.074	0.049	0.099
			5	2007	4	0.014	0.004	0.026
2002	2	6256	2	2004	90	*0.029*	*0.024*	*0.034*
			3	2005	708	0.520	0.481	0.560
			4	2006	361	0.843	0.731	0.971
			5	2007	124	0.626	0.475	0.840
2002	3	720	3	2005	54	*0.206*	*0.158*	*0.262*
			4	2006	92	1.168	0.865	1.631
			5	2007	26	0.943	0.484	2.222
2003	1	2662	1	2004	0	*0.000*	*0.000*	*0.000*
			2	2005	33	0.044	0.031	0.058
			3	2006	154	0.499	0.427	0.596
			4	2007	71	0.370	0.283	0.478

			5	2008	4	0.036	0.010	0.075
2003	2	8692	2	2005	102	*0.028*	*0.023*	*0.033*
			3	2006	1231	1.059	0.983	1.146
			4	2007	587	2.379	1.698	4.006
			5	2008	59	1.151	0.000	3.228
2003	3	3127	3	2006	244	*0.289*	*0.258*	*0.326*
			4	2007	299	0.522	0.461	0.586
			5	2008	38	0.098	0.071	0.128
2004	1	7084	1	2005	2	*0.001*	*0.000*	*0.001*
			2	2006	31	0.018	0.013	0.024
			3	2007	131	0.092	0.079	0.106
			4	2008	67	0.057	0.046	0.069
2004	2	7591	2	2006	69	*0.025*	*0.021*	*0.031*
			3	2007	529	0.267	0.247	0.288
			4	2008	370	0.269	0.243	0.297
2004	3	479	3	2007	35	*0.186*	*0.133*	*0.244*
			4	2008	49	0.381	0.289	0.501
2005	1	9195	1	2006	3	*0.001*	*0.000*	*0.001*
			2	2007	33	0.012	0.008	0.015
			3	2008	101	0.043	0.037	0.051
2005	2	8696	2	2007	117	*0.032*	*0.027*	*0.036*
			3	2008	739	0.268	0.251	0.286

Table 9: Comparison of age-specific fishing mortality rate estimates for a range of scenarios, as described below. F estimates > 0.4 are shaded, and those derived from recaptures in the same year as release are italicized. A dash indicates that more fish were recaptured than predicted to exist in the population.

Scenario 1: reporting rate vector 1 from Table 1 for the surface fishery, natural mortality vector 1 from Table 3, and a reporting rate of 0.65 for the longline fisheries (i.e., same as Table 8).
Scenario 2: same as scenario 1 but with reporting rate vector A4 from Table 1 for the surface fishery.
Scenario 3: same as scenario 1 but with a reporting rate of 0.30 for the longline fisheries.
Scenario 4: same as scenario 1 but with natural mortality vector 2 from Table 3.

					F estimate			
Cohort	Age at release	Number of releases	Age	Year	Scenario 1	Scenario 2	Scenario 3	Scenario 4
1999	2	750	2	2001	*0.000*	*0.000*	*0.000*	*0.000*
			3	2002	0.036	0.043	0.058	0.039
			4	2003	0.255	0.355	0.319	0.297
			5	2004	0.095	0.111	0.166	0.121
2000	1	1921	1	2001	*0.000*	*0.000*	*0.000*	*0.000*
			2	2002	0.006	0.007	0.010	0.006
			3	2003	0.172	0.238	0.195	0.203
			4	2004	0.069	0.079	0.096	0.089
			5	2005	0.019	0.021	0.045	0.027
2000	2	492	2	2002	*0.004*	*0.004*	*0.008*	*0.004*
			3	2003	0.273	0.384	0.315	0.296
			4	2004	0.475	0.605	0.588	0.580
			5	2005	0.447	0.520	0.758	0.672
2000	3	3276	3	2003	*0.155*	*0.218*	*0.164*	*0.156*
			4	2004	0.282	0.330	0.313	0.302
			5	2005	0.153	0.147	0.174	0.176
2001	1	2748	1	2002	*0.000*	*0.000*	*0.000*	*0.000*
			2	2003	0.008	0.010	0.011	0.009
			3	2004	0.213	0.231	0.233	0.252
			4	2005	0.057	0.051	0.072	0.073
			5	2006	0.031	0.025	0.048	0.042
2001	2	5869	2	2003	*0.009*	*0.011*	*0.015*	*0.009*
			3	2004	0.745	0.835	0.832	0.827
			4	2005	0.680	0.631	0.909	0.939
			5	2006	0.543	0.398	1.470	1.220
2001	3	1146	3	2004	*0.580*	*0.642*	*0.645*	*0.582*
			4	2005	0.797	0.694	0.939	0.875
			5	2006	1.530	0.740	2.236	2.906
2002	1	3316	1	2003	*0.001*	*0.001*	*0.001*	*0.001*
			2	2004	0.023	0.024	0.029	0.025
			3	2005	0.114	0.098	0.127	0.134
			4	2006	0.074	0.051	0.092	0.094
			5	2007	0.014	0.012	0.015	0.019
2002	2	6256	2	2004	*0.029*	*0.031*	*0.034*	*0.029*
			3	2005	0.520	0.429	0.563	0.570
			4	2006	0.843	0.452	1.171	1.143
			5	2007	0.626	0.309	1.467	1.543
2002	3	720	3	2005	*0.206*	*0.176*	*0.228*	*0.207*
			4	2006	1.168	0.587	1.324	1.313
			5	2007	0.943	0.363	1.517	1.540

2003	1	2662	1	2004	*0.000*	*0.000*	*0.000*	*0.000*
			2	2005	0.044	0.038	0.053	0.048
			3	2006	0.499	0.308	0.568	0.613
			4	2007	0.370	0.266	0.426	0.559
			5	2008	0.036	0.028	0.073	0.065
2003	2	8692	2	2005	*0.028*	*0.025*	*0.035*	*0.028*
			3	2006	1.059	0.574	1.208	1.204
			4	2007	2.379	0.715	3.954	4.267
			5	2008	1.151	0.142	–	–
2003	3	3127	3	2006	*0.289*	*0.183*	*0.307*	*0.289*
			4	2007	0.522	0.409	0.556	0.565
			5	2008	0.098	0.088	0.115	0.114
2004	1	7084	1	2005	*0.001*	*0.001*	*0.001*	*0.001*
			2	2006	0.018	0.013	0.023	0.020
			3	2007	0.092	0.085	0.107	0.108
			4	2008	0.057	0.064	0.070	0.072
2004	2	7591	2	2006	*0.025*	*0.019*	*0.034*	*0.026*
			3	2007	0.267	0.241	0.290	0.289
			4	2008	0.269	0.303	0.291	0.320
2004	3	479	3	2007	*0.186*	*0.170*	*0.208*	*0.187*
			4	2008	0.381	0.440	0.425	0.410
2005	1	9195	1	2006	*0.001*	*0.001*	*0.001*	*0.001*
			2	2007	0.012	0.011	0.014	0.013
			3	2008	0.043	0.049	0.045	0.050
2005	2	8696	2	2007	*0.032*	*0.029*	*0.036*	*0.032*
			3	2008	0.268	0.312	0.283	0.290

Table 10: First year recaptures of fish released in December in the Great Australian Bight by age of release and fishing year. Estimated percent caught is based on reporting rate vector A1 in Table 1, with no allowance for tag shedding.

Fishing year	Release age	Number released	Number returned	Percent returned	Estimated % caught
2003	1	17	0	0	0
	2	894	19	2.1	3.3
	3	3004	295	9.8	15.3
	4	242	34	14.0	22.0
	5	8	3	37.5	58.6
2004	1	622	0	0	0
	2	3187	82	2.6	5.1
	3	978	251	25.7	51.0
	4	27	7	25.9	51.5
	5	3	0	0	0
2005	1	52	0	0	0
	2	2760	43	1.6	3.9
	3	308	34	11.0	27.9
	4	130	12	9.2	23.3
	5	68	12	17.6	44.6
2006	1	22	0	0	0
	2	1887	21	1.1	3.7
	3	2442	194	7.9	26.2
	4	14	1	7.1	23.6
	5	1	0	0	0
2007	1	5	0	0	0
	2	3023	53	1.8	4.1
	3	281	27	9.6	22.6
	4	0	0	-	-
	5	0	0	-	-

Figure 1: Comparison of fishing mortality rate (F) estimates at ages 3, 4 and 5 obtained from the SRP tagging with those obtained from the 1990s RMP tagging, using reporting rate vector 1 for the surface fishery, natural mortality vector 1, and a reporting rate of 0.65 for the longline fisheries. Estimates for the 1990s tagging were obtained using both the methods described in this paper and a Brownie model that integrates data from all release ages (see text for details).